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PHYSICS OF HEAVY IONS IN THE MAGNETOSPHERE.(U)

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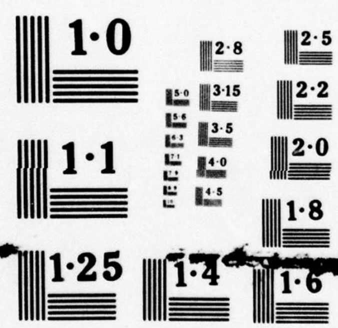
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REPORT SAMSO-TR-78-65

Physics of Heavy Ions in the Magnetosphere

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3 March 1978

Interim Report

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Magnetospheric ions heavier than protons are important as test-particle probes of magnetospheric dynamical processes, but they are at least equally important for the major roles that they (notably He^{+}, He^{++}, and O^{+} ions) play as active participants in natural phenomena. Studies of He^{+} and He^{++} ions of energy $E > 100$ keV yield quantitative information about the mechanisms responsible for magnetospheric radial diffusion. Helium ions at lower energies serve as test particles to distinguish between ionospheric sources and solar sources of

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magnetospheric plasma. Low-energy He^+ ions charge-exchange more slowly than protons of the same energy and may thus become the dominant ionic species in the ring current during the recovery phase of a magnetic storm. In this case they may tend to damp proton-generated electromagnetic cyclotron waves, or they may generate helium-cyclotron waves. Energetic (1-20 keV) O^+ ions are plentiful at low altitudes. They presumably represent ionospheric thermal ions accelerated by auroral electric fields and transported elsewhere by electric convection. At times these oxygen ions may dominate ring-current dynamics, but the observational evidence for this is too limited to be definitive. Heavy ions need not occur naturally to serve either as test probes or as dynamical constituents. Experiments have been carried out (mostly with Ba^+ ions) to trace magnetic field lines and electric convection equipotentials, and other experiments have been proposed to inject (photoionized) Li^+ deep into the magnetosphere as a means of generating electromagnetic cyclotron waves below the lithium gyrofrequency from the free energy that is inherent in the natural pitch-angle anisotropy of ring-current protons. All of the above processes have analogues in the magnetosphere of Jupiter, which is further complicated by the presence of the Galilean satellites, which orbit within the magnetosphere. The satellites represent sources of plasma and neutral "atmosphere" (sputtered off by ion impact) and sinks for magnetically trapped charged particle radiation (either through direct impact or through charge exchange with the "atmosphere"). The observational, experimental, and theoretical study of heavy-ion physics, both terrestrial and Jovian, is still in its infancy, and much work remains for the future.

PREFACE

The authors are pleased to thank Dr. J. B. Blake for an extensive discussion on charged-particle detectors, a discussion that we have summarized in Section I. We are also very pleased to thank Dr. P. F. Mizera for allowing us to use some of his previously unpublished data in our Figure 3, and we are especially grateful to Dr. Mizera for preparing the figure. We thank Dr. F. A. Morse for a discussion on the measurement of brightness in a distant object. We thank Prof. C. F. Kennel and Dr. L. J. Lanzerotti for suggesting the topic of the present review and for their helpful discussions that enabled our topic as thoroughly as we have. We thank Dr. J. B. Blake, Dr. J. F. Fennell, Dr. P. F. Mizera, and Dr. G. A. Paulikas for their helpful comments in the course of the work. Finally, we thank J. B. Kari for her heroic efforts in typing the entire manuscript in such a limited amount of time.

This work constitutes a review article to be published (after revision) in the book <u>Solar System Plasma Physics</u>, edited by C. F. Kennel, L. J. Lanzerotti, and E. N. Parker. The publisher is D. Reidel of Dordrecht.

CONTENTS

FIGURES

FIGURES (Continued)

I. INTRODUCTION

In the early years of radiation-belt research it was natural to focus attention on geomagnetically trapped protons and electrons, since these seemed likely to be the major constituents. People realized that heavier ions must be present as well, but considered the presence of such presumably minor constituents unimportant to the dynamics of radiation belts. The improved satellite instrumentation that has become available in recent years has drastically altered this complacent view. Heavy ions are now recognized to provide a valuable diagnostic probe for identifying magnetospheric source, loss, and transport processes. Moreoever, heavy ions are understood to participate actively in naturally occurring magnetospheric plasma phenomena, and their artificial injection into the magnetosphere in semi-controlled experiments plays a growing role in modern space research.

This review is intended primarily to describe what has been learned, and what can be learned, about magnetospheric processes from the study of heavy ions. There are, of course, additional reasons for studying heavy ions in space, e.g., for understanding nucleosynthesis; for identifying the compositions of the outer planets and their satellites (and of the atmospheres of these bodies); and for analyzing source and loss budgets for minor isotopic constituents of the earth. These questions are assigned only secondary importance here, and some issues (such as cosmic rays and atmospheric chemistry) are not addressed at all.

Having established these priorities, we use the term "heavy ion" to characterize any magnetospheric ion other than a proton, and we restrict our attention to kinetic energies $\lesssim 10$ MeV/nucleon. The important heavy ions that occur naturally in the earth's magnetosphere are He^+, He^{++}, and O^+; ions such as Ba^+ and Li^+ are important for plasma-injection experiments. For Jupiter the important heavy ions are those of Na and S (already observed) as well as those of He and O (and possibly Ne, Mg, and Fe). Ions of C, N, and O (in various charge states) are important for both Jupiter and Earth, but some instruments now available cannot distinguish among these and none can identify the charge state at energies above a few keV/nucleon.

Until recently magnetospheric heavy-ion physics was usually assigned a fairly low priority in satellite and rocket experiments, partly because of the weight and complexity of instrumentation needed to do a good job and partly because of the popular impression that heavy ions had little to do with important magnetospheric processes. In fact, as we attempt to show in this review, there is a great deal to be learned about auroral acceleration processes, radial diffusion, electrostatic convection, ring-current dynamics, sub-auroral red-arc (SAR-arc) formation, and magnetospheric plasma physics in general from the study of heavy ions. In perhaps no other subdiscipline of magnetospheric research is there more of importance to be learned in the future, compared to what is already known.

A note on instrumentation is useful, if only to remind us of two major gaps in the capabilities of instruments that have so far been flown. There are four basic types of instrument, some of which can be combined: (1) threshold detectors (TD's), usually made of silicon (Si), which discriminate heavy ions by their greater dE/dx (energy deposition per unit path length) and which have an effective threshold of a few hundred keV/nucleon for heavy ions; (2) E·dE/dx detectors, which measure dE/dx in a thin detector and E in a thick detector which stops the particle, having a threshold of a few hundred keV/nucleon; (3) electrostatic analyzers (ESA's), followed by momentum or velocity filters, which have an effective upper cutoff ~ 20 keV/charge; and (4) time-of-flight detectors (TOFD's), which must be combined with instruments of other types in order to identify heavy ions. No data have yet been published from the few operational satellite experiments that use TOFD's. The other instrument combinations that have been flown cannot be used in the range from 20 keV/charge to 100 keV/nucleon (approximately), and the identification of charge states has been contingent on restrictive assumptions about the charge and mass composition of the ion sample observed. The advantage of threshold detectors (TD's) is their simplicity. This accounts for their common use in space. Being one-parameter identification systems, however, TD's have less mass resolution and a greater susceptibility to background pile-up than the other (more complicated) detector systems. Thus, TD's cannot reliably distinguish among C, N, and O; moreover, because of background effects, they are not useful if the flux of heavy ions is less than $\sim 10^{-4}$ that of protons.

Despite some of these observational constraints, significant progress has been made in the study of magnetospheric heavy ions, and the future for research in this area is a very bright one indeed. We have organized the remainder of this review into sections that (in order) deal with auroral-magnetospheric processes; heavy-ion tracers for radial diffusion and electrostatic convection; multi-ion plasma physics; artificial plasma-injection experiments; and heavy-ion physics at Jupiter. Finally, a program for the future is outlined in Section VII.

II. AURORAL-MAGNETOSPHERIC COUPLING AND THE O^+ PROBLEM

In 1972 Shelley et al.[141] reported a truly shocking discovery based on their measurements from a low-altitude polar-orbiting satellite, viz., large fluxes of precipitating O^+ ions having energies up to 12 keV (the upper limit of their instrument). These fluxes, ranging up to 0.4 erg/cm^2-sec-ster in energy content, were observed on the night side at L values as low as 2.5 and sometimes exceeded proton precipitation fluxes at the same energy. Since particles having A/Z (mass-to-charge ratio) = 16 in the solar wind are only $\sim 10^{-3}$ as abundant as protons there[8], it is fairly clear that the observed heavy ions were of ionospheric origin.

Further studies[136-139,142,143] have revealed that the observed O^+ ions generally precipitate equatorward of the precipitating protons that accompany them (see Figure 1). The invariant latitudes of the O^+ and H^+ precipitation peaks, i.e., their values of $\cos^{-1}(L^{-\frac{1}{2}})$, are well correlated with each other and with the invariant latitude of the plasmapause, which lies equatorward of both precipitation maxima. Moreover, the precipitating O^+ intensity is well correlated in time with the ring-current intensity (as measured by the geomagnetic index D_{st}) and with substorm activity (as measured by the index AE). The possibility thus exists that O^+ is a significant contributor to the storm-time ring current. Unfortunately there are as yet few trapped-particle measurements that distinguish among ion species in the ring current.

In principle, however, it is possible to decide whether there is indeed a significant O^+ flux among the ring current ions. Because of the fourfold difference in number density required to produce the same flux, a given flux of O^+ ions at any given energy would contribute four times as much to D_{st} as would the same flux of protons; the O^+

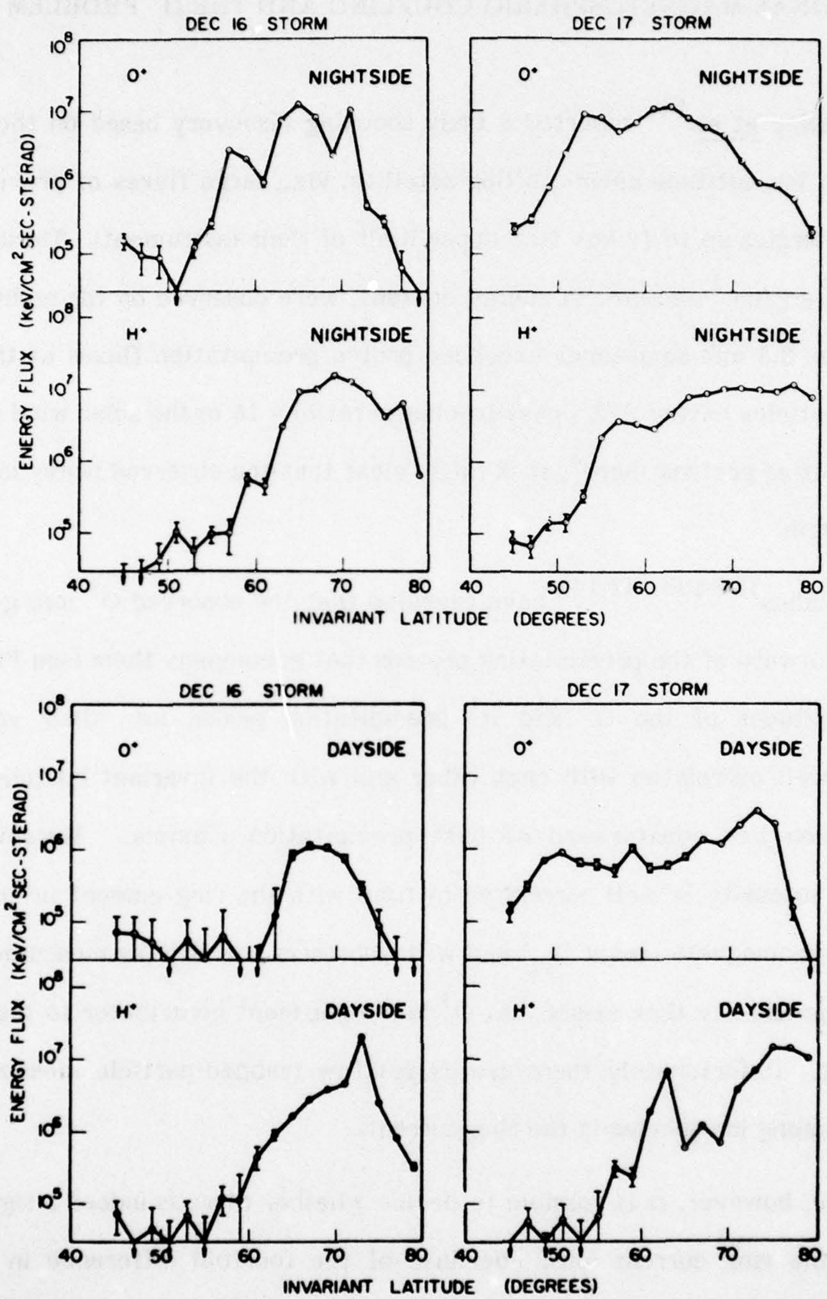


Figure 1. Precipitating energy fluxes, nightside (~0300 LT) and dayside (~1500 LT), associated with two magnetic storms[137].

and H^+ ions would differ by a factor of four in velocity, but their drift rates would be the same. Thus, the D_{st} values calculated from ion fluxes observed at the equatorial satellite S^3 (Explorer 45) under the assumption that these ions were protons would yield discrepancies with D_{st} values, measured at the network of ground stations during the same time period, if there were a significant contribution from O^+ in the ring-current ion flux. For example, a 5% contribution from O^+ in the observed ion flux would result in a 15% greater ion D_{st} on the ground than one would calculate under the assumption of a 100%-proton flux. Of course, one cannot neglect the contribution of ring-current electrons to D_{st} at this level. Berko et al.[12] have carried out such a comparison and have concluded that, during a time period when the Lockheed ESA detected significant precipitation of O^+, at most a few percent of the ring-current ion flux could have arisen from O^+. In view of the compounded uncertainties inherent in such a comparison, however, it would be wise to wait for direct ion-composition measurements in the ring current before closing the door on this question.

The discovery of energetic O^+ was so shocking for two reasons. This was the first reported example of a heavy ion as the dominant component of a magnetospheric plasma, and no one at the time could think of a good mechanism for energizing such heavy ions. The idea of cyclotron-resonant energy transfer (see Section IV) from protons to O^+ has been proposed[22,30] but is not very promising. The idea of charge exchange between energetic protons and atomic oxygen is not very appealing either, since this would tend to produce energetic neutral H and cold O^+. At the time the energetic O^+ was discovered, there had been no direct observations of the parallel (to $\mathbf{B}$) electric fields that might accelerate thermal ionospheric O^+ to energies of several keV. Such parallel $\mathcal{E}$ fields had been contemplated theoretically[1,99,120] and were invoked from time to time in the literature, but the truly compelling argument for their existence was provided by Evans[51] in his elegant analysis of precipitating electrons and their backscatter spectrum.

Moreover, the observational situation has greatly improved since the launch of the S3-3 satellite into an elliptical orbit with polar-region apogee ($\approx$8000 km) and perigee ($\approx$240 km). Using data from their triaxial $\mathcal{E}$-field antenna on S3-3, Mozer et al.[115] have reported perpendicular (to B) electric fields as strong as 400 V/km at an altitude $\approx$7000 km and parallel (to B) electric fields with the smaller, but still unbelievably high, strength of 100-200 V/km. An example of their observational results, after spin-demodulation of the $\mathcal{E}$-field data, is shown in Figure 2. The perpendicular $\mathcal{E}$ field showed a distinctive sign reversal, such as would be produced by a sheet of negative charge, over a latitudinal extent ~100 km at the sites of enhancement in $\mathcal{E}_{\parallel}$ (see Figure 2). This feature is seen[112,144] in association with beams of downgoing electrons and upgoing ions (as well as with unbeamed particles) having energies that range from several hundred eV to a few keV, as is illustrated by the gray-scaled energy-time spectrogram shown in Figure 3 (provided by P. F. Mizera from published[115] and unpublished material, 1977). This figure shows an "inverted-V" structure in the electron data (i.e., a rise and fall in the mean electron energy) quite similar to to those reported by Frank and Ackerson[59,60]. Electron beams are not obvious here, because of decollimation by the earth's magnetic field and contamination by backscatter. However, the ion beams are very distinct, partly because the earth's B field collimates them. A measure of the ionic composition of one such beam[144] is shown in Figure 4. The virtual absence of upgoing helium ions is evident here. Further analysis reveals that the H^+ and O^+ beams are of comparable intensity, ranging up to $\sim 10^8$ cm^{-2}sec^{-1}ster^{-1}keV^{-1} at the peak, which occurs[144] at an energy ~1 keV.

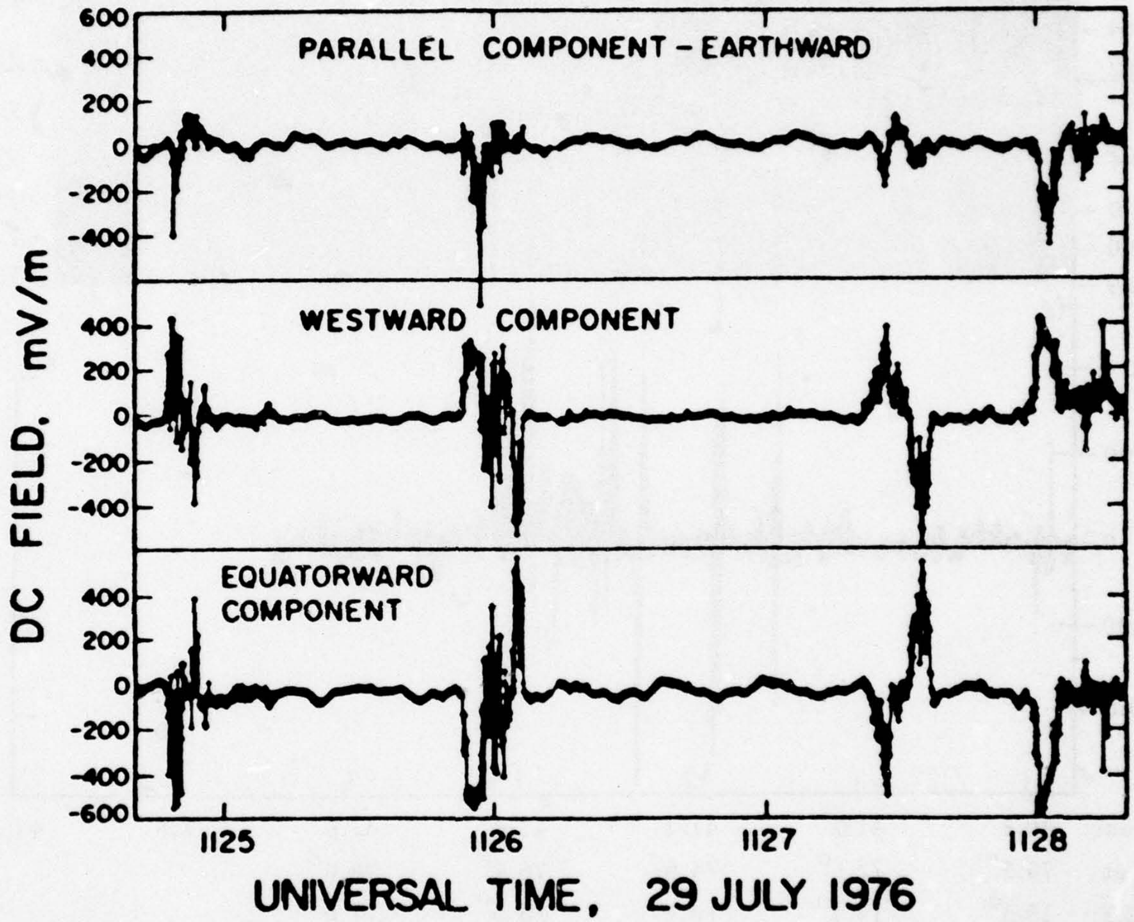
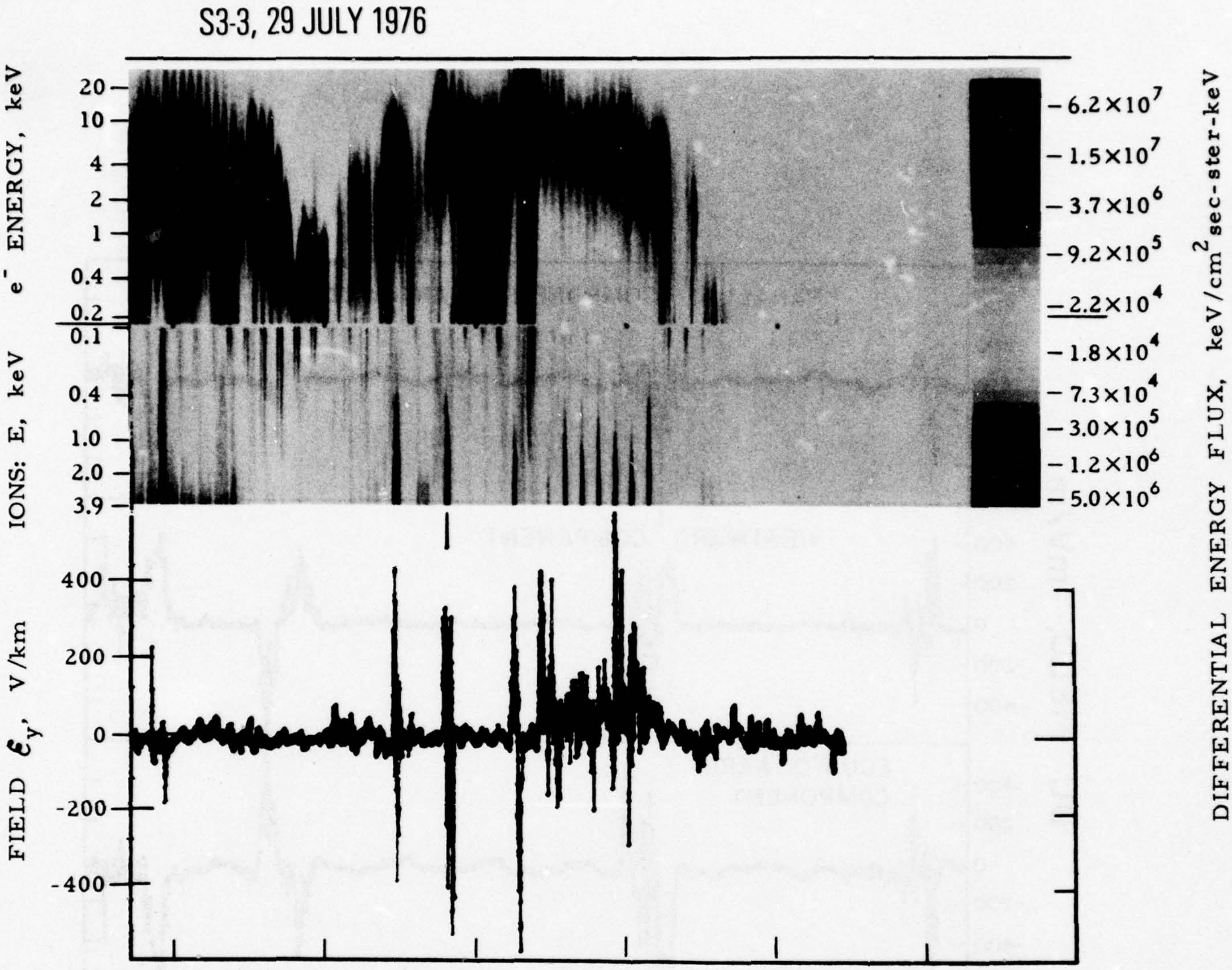


Figure 2. Electric-field components observed at S3-3 on poleward-bound pass through northern auroral zone[115], UT = 41.08—41.30 ksec.



UT, ksec	40.8	41.0	41.2	41.4	41.6	41.8	42.0
Inv Lat	70.5°	72.6°	74.6°	76.4°	78.0°		
Mag LT	19.3°	19.1°	18.7°	18.3°	17.8°		
Alt, km	7274	7472	7641	7782	7893		
$\|B\|$, γ	5940	5770	5630	5510	5410		

Figure 3. Particle spectrograms (P. F. Mizera, personal communication, 1977) and westward electric-field component[115] obtained from S3-3 data during aforementioned pass through northern auroral zone, but over a longer time interval than in Figure 2. Common features are discernible at 1124:50 UT (41.09 ksec), 1126 UT (41.16 ksec), 1127:30 UT (41.25 ksec), and 1128 UT (41.28 ksec).

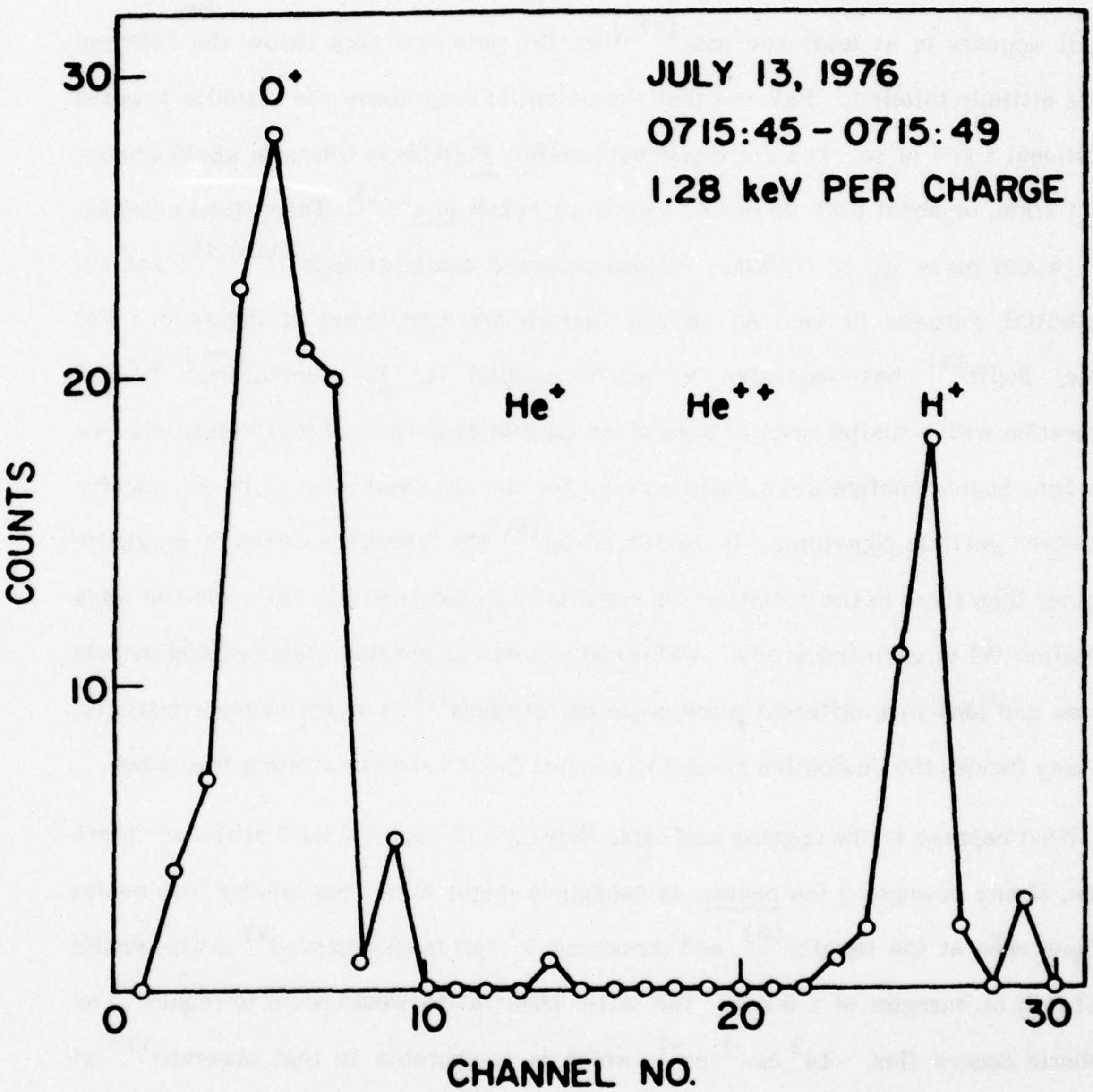


Figure 4. Mass/charge spectrum observed[144] in northern auroral zone on Revolution 35 of S3-3.

Such results are readily interpreted in terms of upward parallel (to $\mathbf{B}$) electric fields; it appears in at least one case[112] that the potential drop below the 7000-km satellite altitude totalled ~ 2 kV and that the potential drop above the satellite totalled an additional 1 keV or so. The corresponding parallel $\mathcal{E}$ fields in this case would amount to ~ 0.3 V/km, or about 0.2% of those reported by Mozer el al.[115]. Theoretical expectations[99] would place $\mathcal{E}_{\parallel} \lesssim 1$ V/km. Various proposed configurations[70,151,152] for the equipotential contours in such an auroral feature are illustrated in Figure 5. For example, Swift[151] has suggested a nearly parallel (to $\mathbf{B}$) electrostatic "shock" configuration with a spatial scale of several ion Larmor radii (tens of km) in latitude (see Figure 5c). Such a configuration could account for the observed reversal in $\mathcal{E}_{\perp}$ and for "inverted-V" particle signatures. In Swift's model[151] the "shock" is driven by energetic ions (other than those in the beams) and is essentially an electrostatic ion-cyclotron wave (see Section IV) at zero frequency. Additional sources of parallel electric field include electrons and ions with different pitch-angle anisotropies[1,29] and anomalous resistivity, which may furnish the dissipation needed to convert Swift's structure into a true shock.

What happens to the upgoing ions after they pass through the S3-3 altitude? There are few, if any downgoing ion beams, as conjugacy might allow, but similar ions beams have been seen at the equator[103], and streaming O^+ has been observed[61] in the earth's magnetotail at energies of 1-5 keV. The latter observation would seem to require[61] an ionospheric source flux ~10^8 cm^{-2}sec^{-1}, which is comparable to that observed[112] at S3-3. Perhaps conjugate upgoing beams thermalize each other through a two-stream instability as they reach the equator in closed field lines[133] while upgoing streams on open field lines escape from the magnetosphere in the manner of polar-wind ions[9].

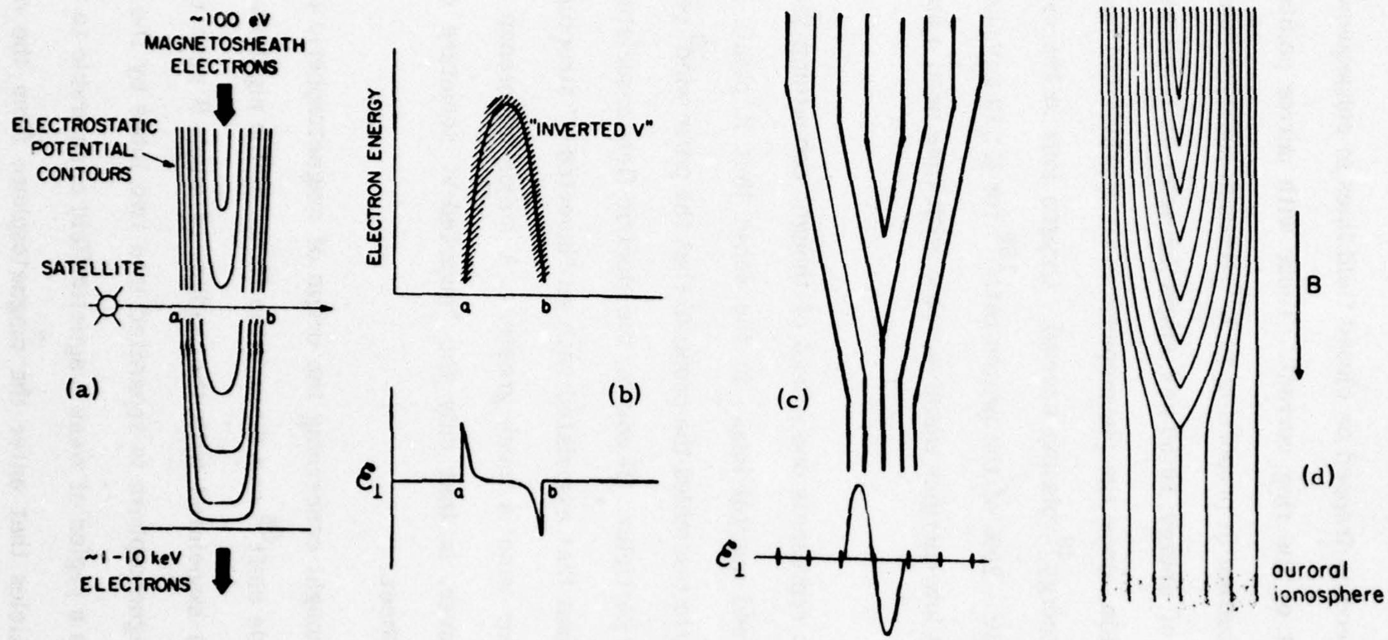


Figure 5. Proposed equipotential configurations (a,c,d) associated with "inverted-V" structure on energy-time spectrogram (b). Panels (a) and (b) summarize the early ideas of Gurnett[70]; panel (c) is based on the electrostatic-shock model of Swift[151]; panel (d) is taken from a more recent paper by Swift et al.[152]; it combines some of the features that were present separately in (a) and (c).

Reconnection and convection may introduce some ambiguity in the above alternatives. Ions of energy 1-5 keV that become trapped on closed field lines in consequence of such processes would become part of the ring current. Those with mirror points near the equator are subject to energization in proportion to L^{-3} through sunward convection or radial diffusion. Thus, ions of energy 10-50 keV might be seen at L values near the plasmapause (but not far inside, since the plasmapause is an approximate boundary for low-energy[117] and medium-energy[40] plasma access). Oxygen ions in the ring current would charge-exchange at only $\sim 20\%$ of the proton rate[156] for $E \lesssim 10$ keV, and so their fraction of the ring current at low energies would increase with time until a steady state is attained (see Section IV).

The foregoing scenario represents one school of thought concerning the origin of ring-current, radiation-belt, and auroral ions. In the sense that it points toward an ionospheric source, this scenario resembles the proposal that the polar wind[9] provides the plasma sheet with its charged particles. Of course, the electric field associated with the polar wind is much weaker than that associated with an "inverted-V" structure, but the latitudinal extent of the polar wind is much greater. A major difference related to electric-field strength, however, is that only the "inverted-V" structure can supply significant O^+ to the plasma sheet.

The other school of thought concerning the origin of magnetospheric ions is that they enter through the dayside cleft[58] and through the flanks of the nightside magnetopause. The dayside cleft is associated with the regions of weak B near the neutral points[105]. The nightside magnetosphere is separated into two lobes by the equatorial current sheet, which occupies a region of weak magnetic field comparable to that of the dayside cleft. Charged particles that enter the magnetosphere from the outside are mainly of solar origin.

The above considerations represent a major dilemma[6] in magnetospheric physics: Do energetic particles in the ring current, radiation belts, and aurora have their main source in the ionosphere or in the solar wind? Axford[6] had proposed isotopic and charge-state observations on helium ions in the magnetosphere as a way to identify the dominant source, since the He^{++}/He^{+} and the He^{3}/He^{4} abundance ratios are much greater in the solar wind than in the ionosphere. Such measurements have since been made in diffuse proton auroras (which are quite different from the well localized visual auroral arcs associated with "inverted-V" structures in electron spectrograms and with upgoing ion beams) and also during auroral break-up. A 1973 review of such measurements has been provided by Reasoner[125], who (following Cornwall[34,35]) has indicated the need for caution in interpreting charge-state results when atmospheric collisions may have intervened between the source and the observer (see Section III). Whalen et al.[170,171] used an ESA (see Section I) and momentum filter (magnetic deflection system) on a rocket flight to distinguish between He^{+} and He^{++} among precipitating ions in diffuse proton auroras. They found no statistically significant abundance of He^{+} compared to He^{++} and therefore concluded that the source was solar rather than ionospheric. The precipitating ion flux was $\sim 10^{5}$ $cm^{-2}sec^{-1}ster^{-1}keV$, or less than $\sim 1\%$ of the upgoing ion flux found in association with "inverted-V" structures. Similar results were found by Sharp et al.[135] in satellite passes through the auroral zone. Recoverable metal foils have been flown on auroral rockets and analyzed with a mass spectrometer to ascertain the He^{3}/He^{4} abundance ratio[7], which turned out during an auroral break-up to approximate that of the solar wind[27]. These results provided additional support for the hypothesis of a solar (rather than ionospheric) source.

However, He^+ has been found precipitating in the auroral zone during a storm[83] at a flux level $\sim 10^7$ $cm^{-2}sec^{-1}ster^{-1}keV^{-1}$ for energies of a few keV. This level exceeded that of the precipitating H^+ and O^+ fluxes in an auroral event that yielded no detectable He^{++}. The ions seen in this instance were probably not of solar-wind origin: both the He^+/He^{++} and the O^+/H^+ ratios were characteristic of the ionosphere. Thus, the observational situation seems to be somewhat variable. Further opportunities to identify the source of auroral, ring-current, and radiation-belt ions are potentially available from a study of ions heavier than helium. Krimigis et al.[95], for example, have found that ions having $Z \geq 3$ are $\sim 10^{-3}$ as abundant as helium ions having the same energy/nucleon. The challenge[13] is to distinguish such heavy ions ($A \geq 12$) from each other at $E/A \leq 1$ MeV/nucleon; determination of the C/O abundance ratio in this range should provide the most decisive possible test for identifying the particle source, since this ratio is larger by at least a factor $\sim 10^5$ in the solar wind than in the ionosphere[13].

III. HEAVY IONS AS PROBES FOR MAGNETOSPHERIC PROCESSES

Before the discovery of energetic O^+ ions in great numbers[141], the only known role for heavy ions in magnetospheric processes was to serve as test particles to probe the dynamics of protons. By studying heavy ions one hoped to discover the primary source of radiation-belt particles, as well as the mechanisms by which they are injected into the region of closed field lines, transported across L, and energized. Of course, heavy ions are now of intrinsic interest also, aside from their historic role as test particles.

The earliest quantitative observations of trapped helium ions are those reviewed by Krimigis[92,93] and by Blake and Paulikas[16]. The data were taken from low-altitude satellites in polar orbits, i.e., from a TD on Injun 5 and from an $E \cdot dE/dx$ telescope on the OV1-19 satellite. The orbits precluded the generation of a profile in L for particles mirroring near the equator. Many later observations shared this drawback[17,57,94]. Representative off-equatorial proton and helium-ion spectra[57] are shown in Figure 6 with the indicated normalization. The instrument was unable to distinguish He^+ from He^{++}; the term "alpha particles", as commonly used in this context, includes both charge states. The proton and alpha spectra corresponding to the same L and B/B_o (ratio of local to equatorial field intensity on a given field line) in Figure 6 seem to obey the same asymptotic power law. The index in the power law would therefore be unaltered if one plotted flux against energy per nucleon (E/A) or energy per charge (E/Z), rather than energy per entity (E) as is done in Figure 6. However, the normalization would be altered. A comparison of these three conventions as they affect the ratio $J_\perp^\alpha/J_\perp^p$ is

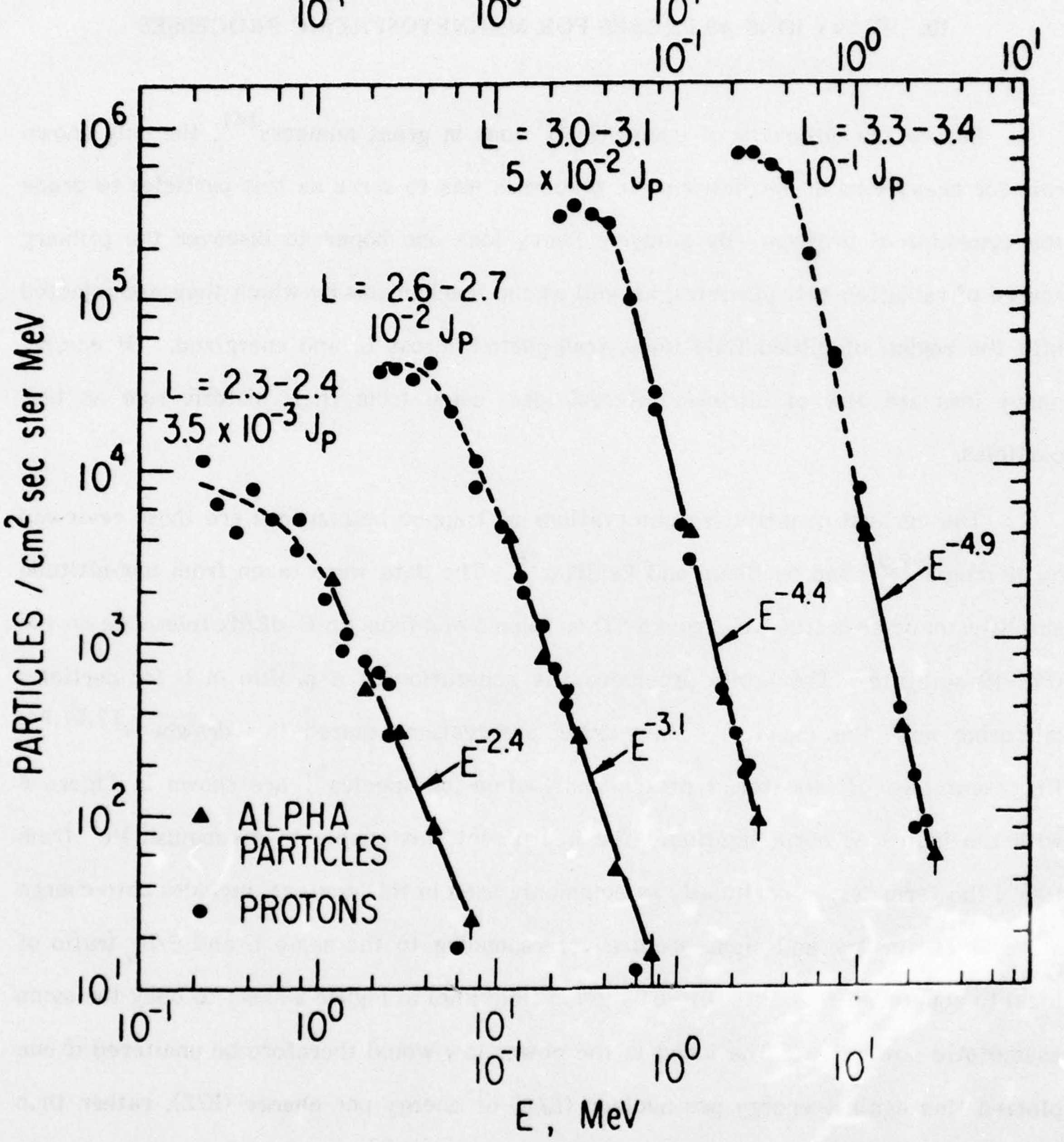


Figure 6. **Differential alpha-particle and renormalized proton spectra[57] from OV1-14 (1968-26B) at selected off-equatorial locations (from $B/B_o = 2.28$ at $L = 2.3$ to $B/B_o = 8.48$ at $L = 3.3$). The indicated renormalization factors represent the α/p ratio at fixed E, rather than at fixed E/A.**

shown[94] in Figure 7 for alpha-particle energies in the range 1-8 MeV. A certain dynamical significance corresponds to each convention. For example, Tverskoi[159] and Hess[79] had predicted, on the basis of a theory to be discussed below, that the α/p flux ratio at fixed energy/nucleon (E/A) should be near the solar-wind ratio, which is found[81] to be $\sim 4\%$. The actual α/p ratio at fixed E/A turns out to be ~ 100 times smaller than this, at least for the off-equatorial observations summarized in Figure 7.

Analysis of quiet-time Injun-5 measurements on CNO ions[95,162] revealed a similar puzzle: the CNO/He ratio at $E/A \gtrsim 0.3$ MeV/nucleon was only $\sim 10^{-3}$ in the magnetosphere, as compared with $\sim 10^{-2}$ in either the solar wind or the ionosphere. Thus, the CNO/H ratio is ~ 1000 times smaller in the off-equatorial magnetosphere than in the solar wind during quiet times. It would have been extremely valuable[13] to distinguish among the separate species C, N, and O, but this was not possible with the TD aboard Injun 5. Carbon and oxygen have been measured separately in the radiation belts at much higher energies (13-33 MeV/nucleon). The resulting quiet-time O/C ratio of 0.5 ± 0.4 is consistent only with an extraterrestrial source[113]. Unfortunately, it has been impossible to establish the CNO/He ratio reliably. Verzariu[163] has reported observing a CNO/He ratio $\sim 10^{-2}$ in the magnetosphere following a solar-particle event in which the magnetospheric CNO flux increased by a factor ~ 100 compared to quiet-time levels.

The general impression of having too few magnetospheric heavy ions was changed considerably when equatorial measurements became available[15,56,64]. It then became clear that the equatorial pitch-angle distribution of helium ions is considerably narrower than that of protons, which would imply that the α/p ratio is a sharply decreasing function of magnetic latitude. An example[15] from the inner zone ($L \lesssim 2$) is shown in

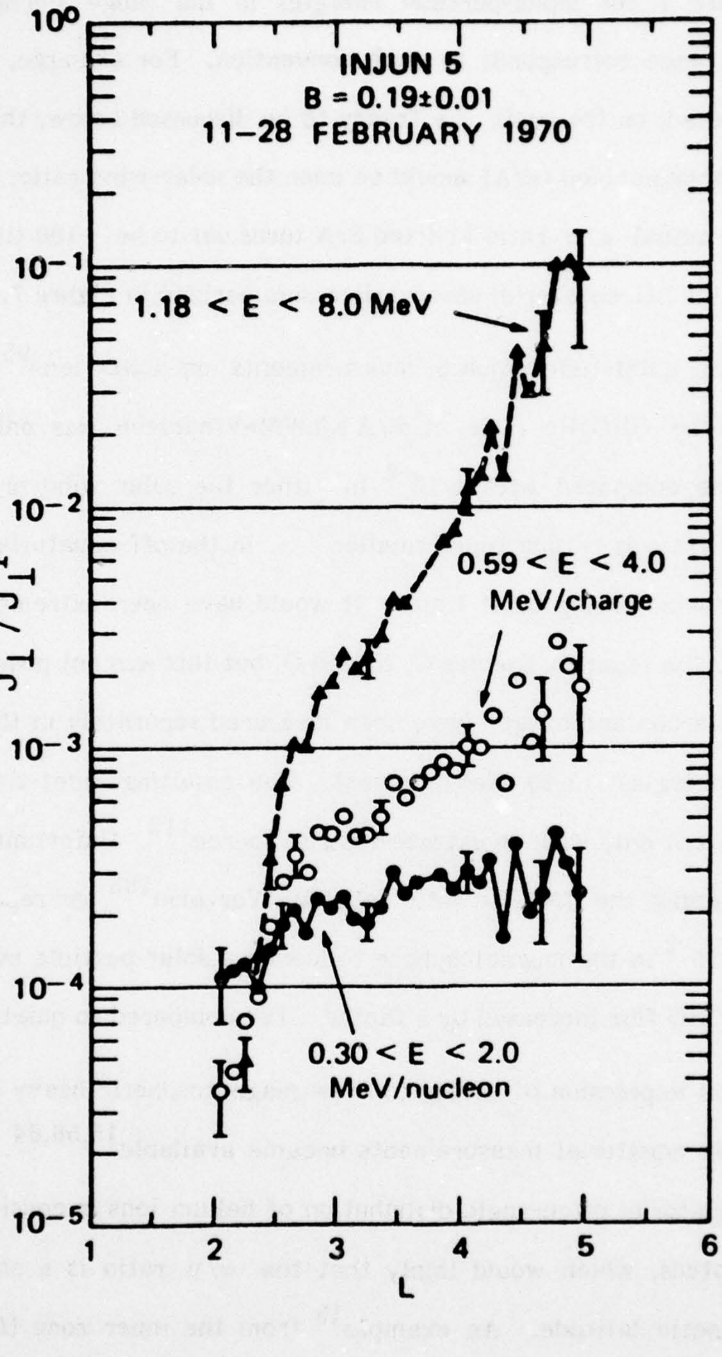


Figure 7. Observed α/p ratios[94] at fixed E, fixed E/Z, and fixed E/A: magnetic latitude of observation increases strongly with L.

Figure 8, where a fit to distributions of the form $\sin^n \alpha_0$ yielded n = 6.7 for protons and n = 11.3 for helium ions. Fritz and Williams[64] report $n \approx 8$ for outer-zone ($3 \leq L \leq 5$) alpha particles and $n \approx 5$ for outer-zone protons at E/A $\approx$ 0.2-0.5 MeV/nucleon. They find α/p ratios approaching 10^{-2} at the magnetic equator, in rough agreement with solar-wind and ionospheric values. Figure 9 shows that the pronounced variation of the α/p flux ratio with equatorial pitch angle (hence, magnetic latitude) is rather insensitive to L over a certain range of L values[56]. It would have been difficult to sort out any such variation from Figure 7 (above), since B/B_0 there was an increasing function of L rather than a constant parameter of the profile.

There exist major temporal variations in the α/p ratio. Magnetic storms and substorms cause it to increase by as much as an order of magnitude far off the equator, but by far less at the equator itself. For E/A $\gtrsim$ 0.2 MeV/nucleon the alpha-particle intensity far off the equator decays more slowly than would be predicted from the theory of ionic collisions with the atmosphere (which theory entails primarily energy deposition and charge exchange) following a magnetic storm. This finding suggests a role for pitch-angle diffusion by wave-particle interactions (see Section IV). It has already been mentioned that magnetospheric CNO fluxes may increase by two orders of magnitude during a magnetic storm. Evidently the injection, transport, energization, and loss process depend in important ways on Z and A.

Until 1971 the only theoretical framework available[79,159] for analyzing such results for E/A $\gtrsim$ 0.2 MeV/nucleon was one that postulated a universal radial diffusion coefficient D_{LL} (independent of E, Z, and A) and a sole source originating in the solar wind. The radial diffusion was supposed to be caused by magnetic impulses that are step-like on the drift time scale. It was assumed that injection into the magnetosphere at

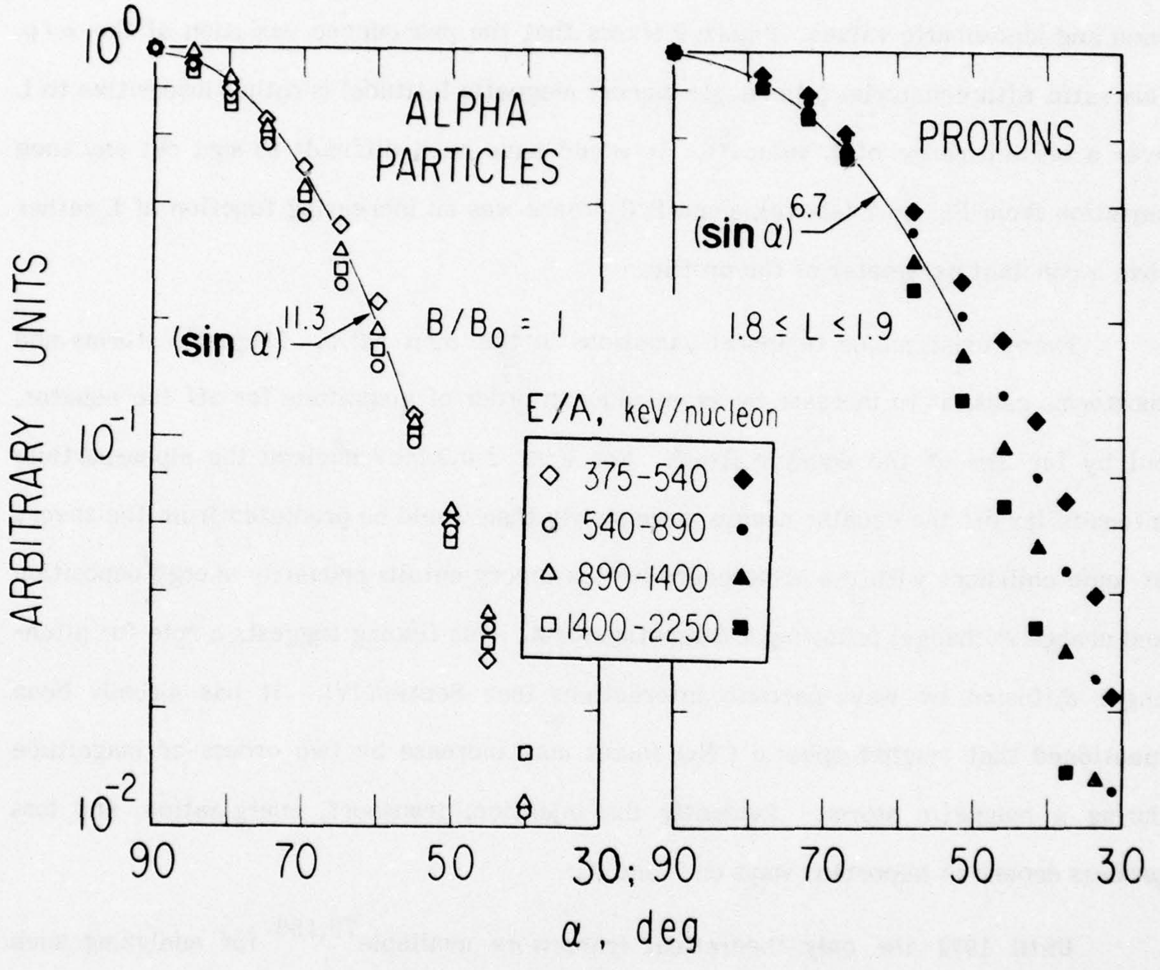


Figure 8. Equatorial pitch-angle distributions of alpha particles (left panel) and protons (right panel) from OV1-19 (1969-26C) data[15].

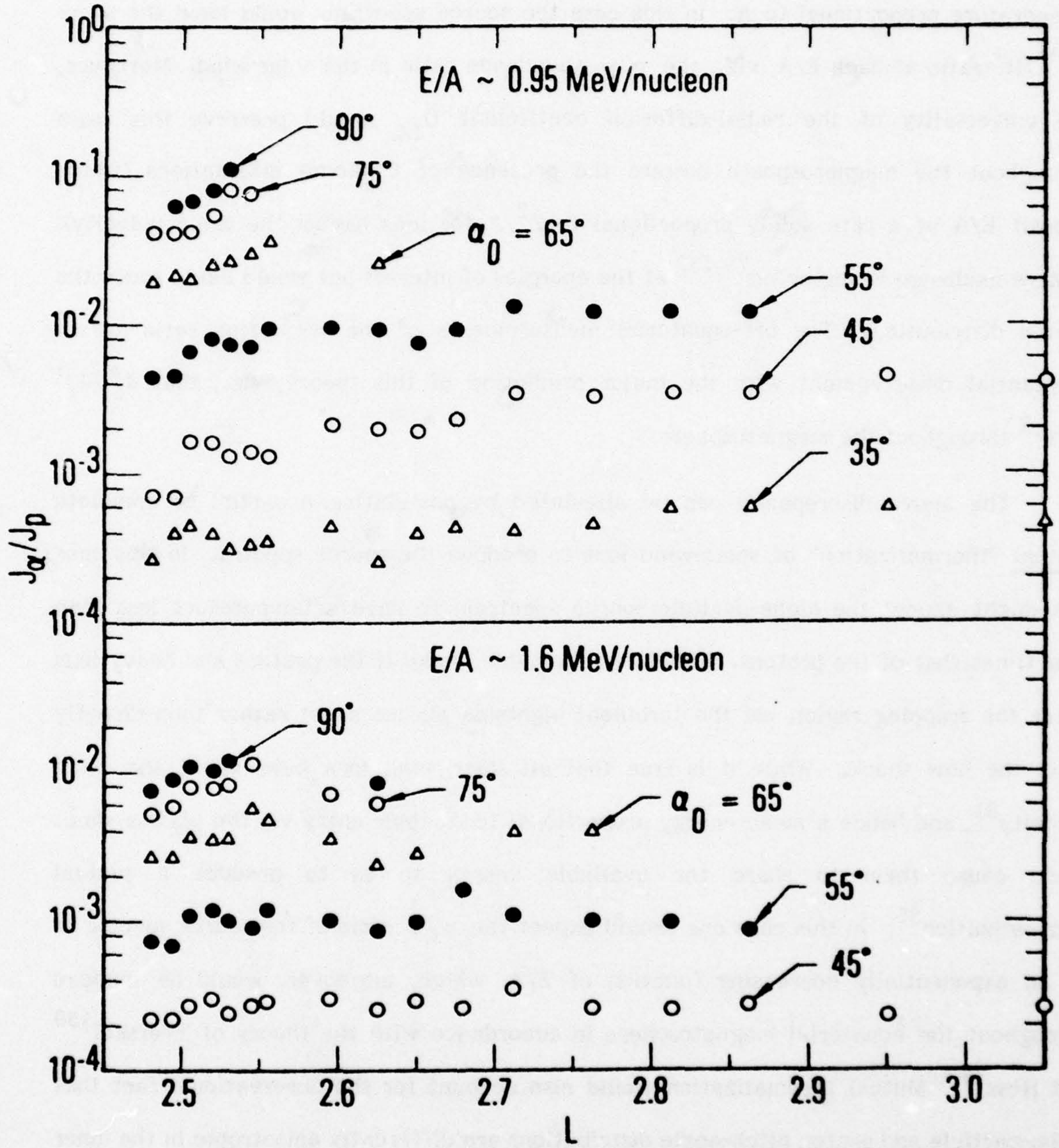


Figure 9. Observed α/p flux ratios at fixed E/A, equivalent to $J_{\perp}^{\alpha}/J_{\perp}^{p}$ at $B/B_o = \csc^2 \alpha_o$, as compiled[56] from the data of various spacecraft instruments.

$L \gtrsim 7$ somehow separately "thermalized" the various solar wind ions so as to produce a temperature proportional to A. In this case the source spectrum would have the same He^{++}/H^{+} ratio at each E/A, viz., the α/p abundance ratio in the solar wind. Moreover, the universality of the radial-diffusion coefficient D_{LL} would preserve this ratio throughout the magnetosphere despite the presence of Coulomb interactions (which deposit E/A at a rate solely proportional to Z^2/A for ions having the same velocity). Charge exchange is neglected[79,159] at the energies of interest but would likely erode the proton distribution. The off-equatorial measurements of the α/p flux ratio are in substantial disagreement with the major prediction of this theory, viz., that $J_{\perp}^{\alpha}/J_{\perp}^{p} > 10^{-2}$ throughout the magnetosphere.

The above discrepancy can be alleviated by postulating a partial or complete <u>mutual</u> "thermalization" of solar-wind ions to produce the source spectra. In this case one might expect the alpha-particle source spectrum to have a temperature <u>less</u> than four times that of the protons. This is a reasonable model if the protons and heavy ions enter the trapping region via the turbulent nightside plasma sheet rather than directly from the bow shock. While it is true that all solar wind ions have about the same velocity[81], and hence a mean energy proportional to A, their entry via the plasma sheet could cause them to share the available energy so as to produce a mutual thermalization[35]. In this case one should expect the α/p ratio of the source spectra to be an exponentially decreasing function of E/A, which, moreover, would be mapped throughout the equatorial magnetosphere in accordance with the theory of Tverskoi[159] and Hess[79]. Mutual thermalization would also account for the observational fact that alpha-particle and proton pitch-angle distributions are differently anisotropic in the inner magnetosphere (see Figures 8-9, above). The source of extreme anisotropy in either species resides in the fact that radial diffusion from an external source energizes particles by a factor that varies inversely with mirror latitude[116]. Thus, as compared with particles that mirror on the equator, those that mirror at higher latitude must have enjoyed a higher E/A in the source spectrum in order to have the same energy/nucleon at an interior L value. Thus, the steepness of the source spectrum manifests itself as an anisotropy in the equatorial pitch-angle distribution at interior L values. This is true for either species. However, with partial or complete mutual "thermalization" accomplished, the source spectrum for alpha particles is steeper with respect to E/A than the source spectrum for protons. Therefore, the alpha particles show an even larger anisotropy at interior L values than do the protons[131].

The actual situation is much more complicated than this. Ions having E/A $\sim$ 0.2 MeV/nucleon at L $\approx$ 2-3 may have had energies as low as 20 keV/nucleon in the source spectrum at the site of injection (nominally L = 7); if the first two adiabatic invariants are conserved in the process, as is assumed, then the nonrelativistic energy varies as L^{-3} for $\alpha_o = 90^\circ$ and as L^{-2} in the unattainable limit $\alpha_o = 0$. The variation of E/A with L is more complicated at intermediate values of α_o, since α_o itself then varies with L. At energies such as 20 keV/nucleon it turns out that charge exchange is a very important loss (neutralization) process that depends strongly on Z and A; moreover, charge exchange efficiently converts He^{++} to He^{+} at such low energies[31,34,156], as can be seen from Figure 10. One also expects wave-particle interactions (see Section IV) to cause pitch-angle diffusion of both protons and alpha particles, but wave-particle interactions can act with vastly different strengths on the various ionic species if the interactions are cyclotron-resonant. Finally, radial diffusion by fluctuations of the electric "convection" field, such as might occur during substorms, is a very important process to consider, and

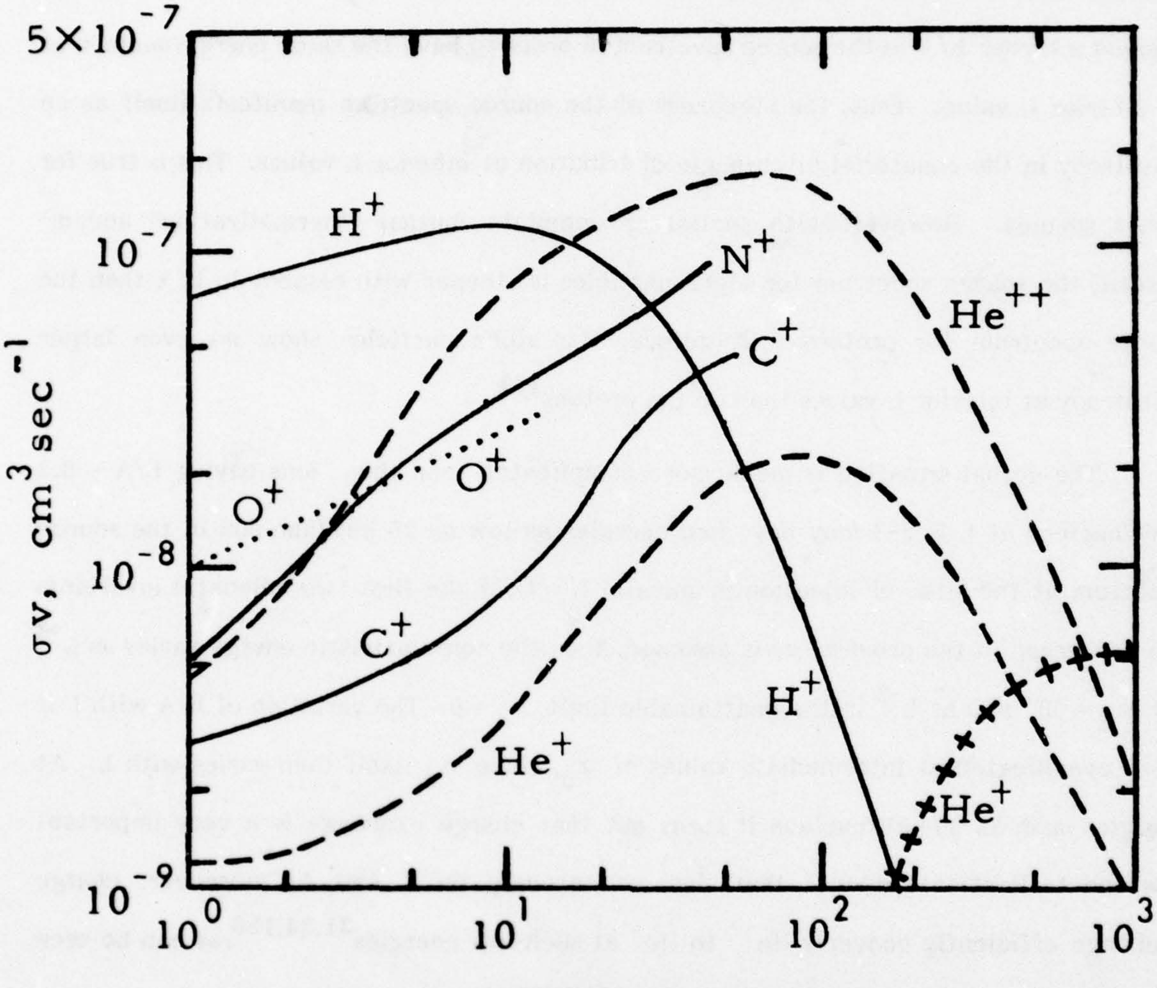


Figure 10. Products of ion velocity and cross section for charge exchange in atmosphere of atomic hydrogen, based on compilations by Claflin[31] and Tinsley[156].

its coefficient has a strong dependence on the ratio of E/A to Z/A, i.e., on E/Z. It was shown by Cornwall[34] that such electrostatic radial diffusion produced a somewhat better fit to the proton data then available than did the type of radial diffusion caused by step-like magnetic impulses, and by Gregory[69] that charge exchange could strongly affect pitch-angle distributions. Cornwall[35] subsequently attempted to include most of the above effects (as well as Coulomb loss and magnetic radial diffusion) in a detailed calculation of the magnetospheric transport and loss of helium ions and protons.

The electrostatic and magnetic diffusion coefficients are each proportional to a spectral density of $c\mathcal{E}/B$, evaluated at the azimuthal-drift frequency of the particle in question[54]. The azimuthally asymmetric component of the $\mathcal{E}$ field induced by step-like changes in B has a flat spectrum, since the corresponding $\partial B/\partial t$ consists of a random series of Dirac delta functions in time. Moreoever, the azimuthally asymmetric component of this $\mathcal{E}$ varies as r^2, since its curl must be proportional to time derivative of a B-field perturbation that increases linearly[105] with the geocentric distance r. Since the main (dipolar) B field in $c\mathcal{E}/B$ varies as r^{-3}, the result is a radial-diffusion coefficient $D_{LL}^{(m)}$ proportional to L^{10} and independent of drift frequency (since the spectrum of $\mathcal{E}$ is flat). A more detailed analysis[54,91] designed to account for the correct mapping of $\mathcal{E}$ and B throughout the magnetosphere introduces in $D_{LL}^{(m)}$ a factor that depends strongly upon the mirror latitude of the particle, i.e., upon α_o. The electrostatic impulses that generate $D_{LL}^{(e)}$ are assumed to result from an equatorially uniform $\mathcal{E}$ field that rises sharply at random times and subsequently relaxes toward its mean value with a decay time $\tau \sim 20$ min. The corresponding spectrum is flat for drift periods $2\pi/\omega_D \gg 2$ hr and inversely proportional to ω_D^2 for drift periods $2\pi/\omega_D \gg 2$ hr. The drift frequency itself is proportional to M/L^2Z for particles of first adiabatic invariant (magnetic moment) M that mirror near the magnetic equator, and there is a <u>weakly</u> inverse variation of ω_D with mirror latitude for particles having the same kinetic energy E. Thus, the spectral density of $c\mathcal{E}/B$ at ω_D is roughly proportional to L^6 for $2\pi/\omega_D \gg 2$ hr and to $L^{10}(Z/M)^2 \sin^4\alpha_o$ for $2\pi/\omega_D \ll 2$ hr. Cornwall[35] has summarized these considerations by setting

$$D_{LL} = D_{LL}^{(e)} + D_{LL}^{(m)}$$

$$= \{ 10^{-5} K [L^4 + (\tau/20 \text{ min})^2 (E_7/Z)^2]^{-1}$$

$$+ 2 \times 10^{-10} \} L^{10} \text{ day}^{-1} \tag{1}$$

for particles that mirror near the equator, where E_7 is the kinetic energy (in keV) at $L = 7$ (or equivalently, the magnetic moment in MeV/G) and $1.3 \leq K \leq 13$. These values have subsequently been endorsed (with $K = 2.6$) by Spjeldvik[148] in his analysis of proton data, but other investigators[32,46,55] prefer a much larger magnitude for $D_{LL}^{(m)}$, perhaps $5\text{-}10 \times 10^{-9} L^{10}$ day^{-1}.

For particles having the same value of E_7/A ($\gtrsim 40$ keV/nucleon) it is evident from (1) that $D_{LL}^{(e)}$ is roughly proportional to $L^{10}(Z/A)^2$ for $L \lesssim 7$. Thus, the electrostatic radial diffusion coefficients for $H^+:He^{++}:He^+$ bear the ratios 16:4:1. Since charge exchange acts quite rapidly (on the diffusion time scale) to convert He^{++} into He^+ (see Section IV), the net result is that helium ions diffuse much more slowly from the external ($L \approx 7$) source than do protons, and so the helium ions have (on the average) more time to be lost (from whatever cause) than do protons before reaching the inner magnetosphere ($L \approx 2\text{-}3$). This condition is somewhat mitigated by the fact that <u>loss</u> rates due to charge exchange ($He^+ \rightarrow He^0$) and Coulomb interactions (deposition rate of E/A proportonal to Z^2/A) are larger for protons than for He^+ at the same E/A.

Figures 11 and 12 show some of the result of Cornwall's numerical calculation[35]. Figure 11 illustrates how efficiently charge exchange has increased the He^+/He^{++} ratio from zero at the source ($L = 7$) to ~ 1 at $L \leq 4$. The calculation has included the cross section for $He^+ \rightarrow He^{++}$, which overtakes the other two helium-ion charge-exchange cross sections[31] at a kinetic energy ~ 1 MeV. In order to avoid economic difficulties that seemed to threaten at the time, Cornwall[35] considered only particles of vanishing second invariant J (i.e., particles mirroring at the magnetic equator) in his numerical work. This was unfortunate, since the only observed α/p ratios then available for comparison had been obtained far off the equator. These were the α/p ratios $\sim 10^{-4}$ provided by the low-altitude measurements discussed above. Several parameters of the model were adjustable, e.g., the parameters K and τ in (1) and the postulated degree of mutual ionic "thermalization" (see above) at L = 7, and it was not very difficult to achieve a fit of the equatorial theory to the off-equatorial data. An example is shown in Figure 12, for which the data points were provided by Krimigis[92]. The data points thus correspond to L values beteen 2.5 and 3.5 and B values in the range 0.18-0.22 G; better resolution than this was unavailable at the time.

Except for the fact that prohibitive computing costs precluded analysis of more than a single value of J, extension of the above-described work[35] to particles of constant (but nonvanishing) J^2/M would have entailed no insurmountable difficulty. It would have been necessary to have averaged the atmospheric density over bounce motion as well as drift in order to determine the Coulomb and charge-exchange loss rates, but this had already been done[43]. One would have to keep track of the variation[134] of the equatorial

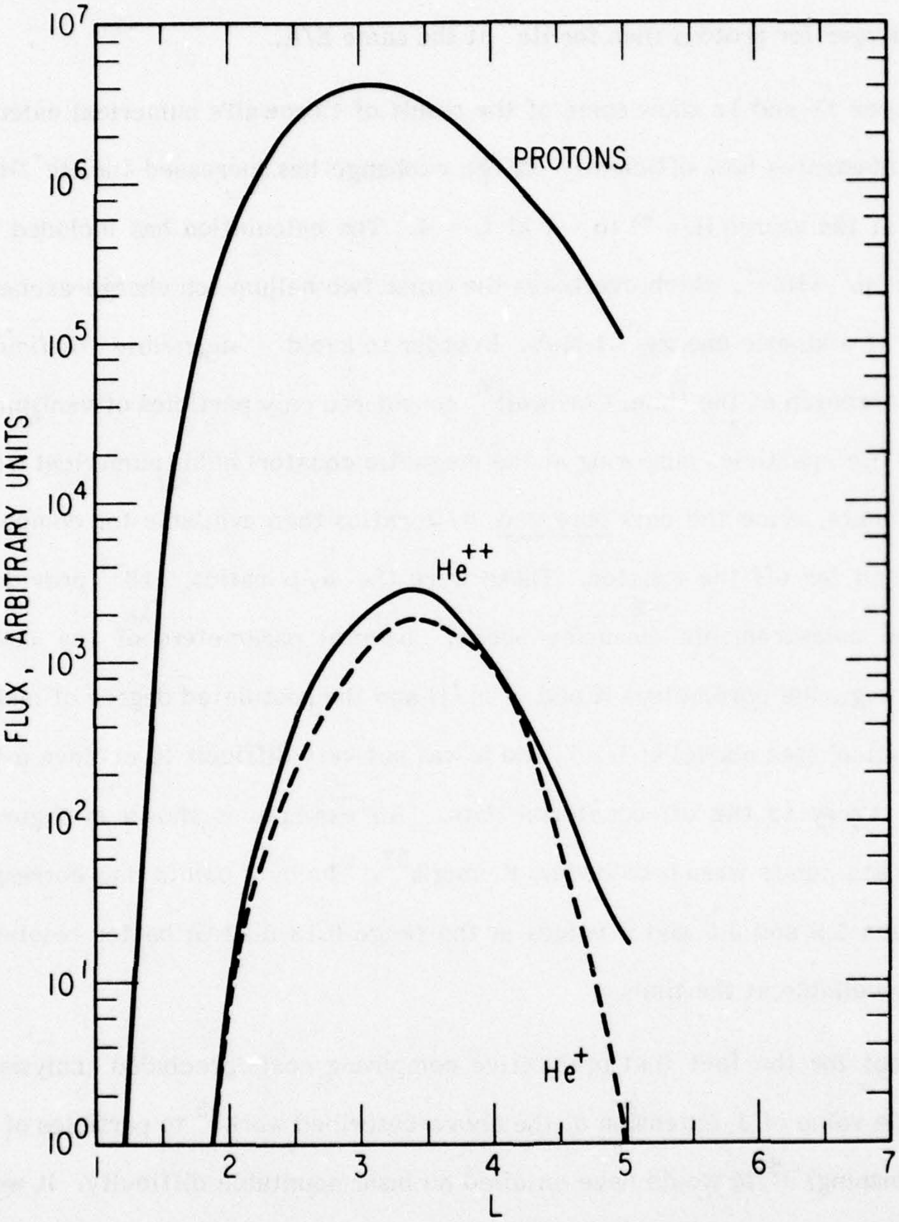


Figure 11. Relative helium-ion and proton flux profiles predicted for E/A = 0.5 MeV/nucleon by Cornwall[35] for K = 10, τ = 20 min, $T^{\alpha} = 2T^{p}$ at L = 7, and a doubled charge-exchange loss rate.

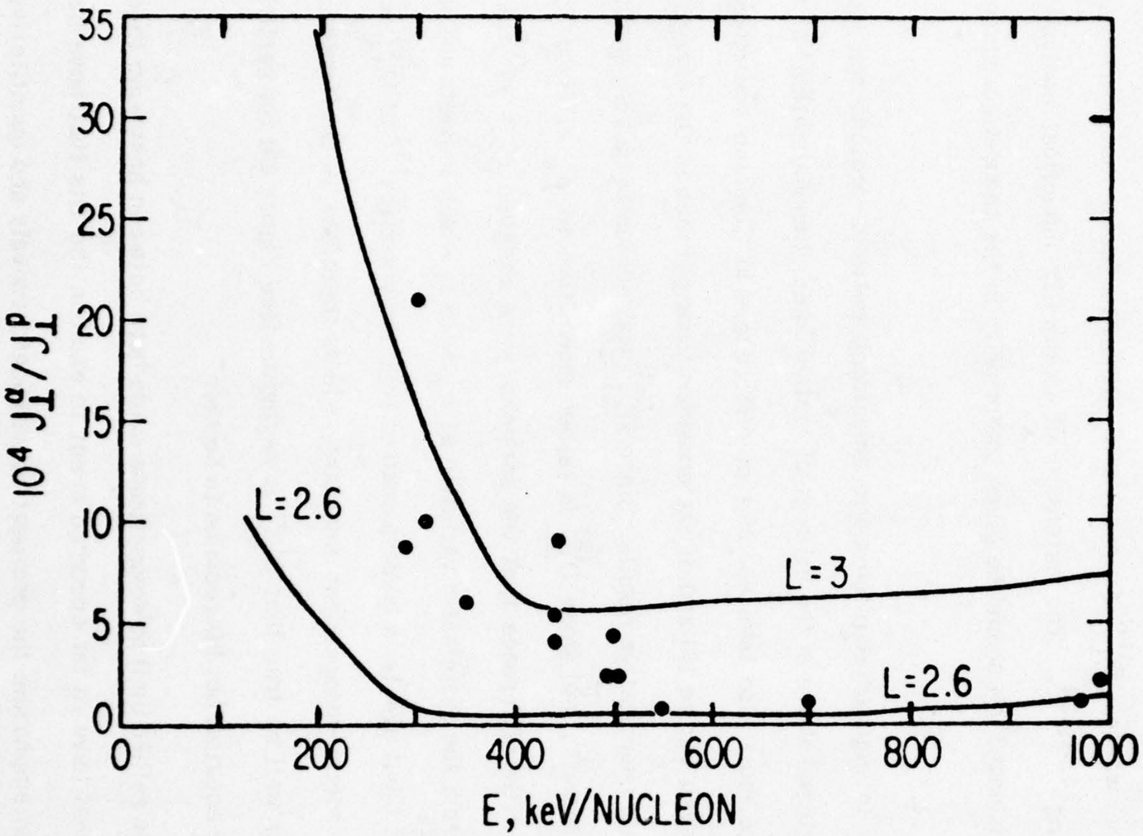


Figure 12. Equatorial α/p flux ratios predicted by Cornwall[35] for K = 3, τ = 40 min, $T^\alpha = 4T^p$ at L = 7, and normal charge-exchange loss rate. Data points are those compiled by Krimigis[92] from off-equatorial observations.

pitch angle α_o and kinetic energy E with L at fixed J^2/M, and one would need to take account of the variation[57,134] of D_{LL} with α_o (see Figure 13), as well as with E and L. It turns out (as was noted above) that $D_{LL}^{(e)}$ depends on E/A, Z/A, and α_o only through the drift frequency $\omega_D/2\pi$, whereas $D_{LL}^{(m)}$ depends on α_o through a factor that is associated with drift-shell tracing[54,91,134]. The extension of Cornwall's numerical analysis to particles with nonvanishing J^2/M should be given top priority in the theoretical study of ionic radiation belts.

The difference in equatorial pitch-angle anisotropy between protons and alpha particles has been discussed above in the context of mutual ionic "thermalization" at the source. However, one must also take account of differences in Coulomb and charge-exchange loss rates (recall Figure 10) and of the considerations outlined in the paragraph above in order to obtain quantitative results. Since $D_{LL}^{(m)}$ was chosen to be very small in Cornwall's numerical work[35], and since $D_{LL}^{(e)}$ is rather insensitive to α_o at fixed E, it might seem to make little difference that the particles were assigned $\alpha_o = 90^o$ there. The difficulty arises from the systematic variation of α_o with L, which impacts not only the variation of E with L but also (as a consequence of this) the variation[134] of $D_{LL}^{(e)}$ with L at fixed J^2/M (an energy-independent invariant, which therefore is unaffected by Coulomb loss). It may well be true that $D_{LL}^{(m)}$ is negligible (see Figure 13) for particles that mirror far off the equator, but his remains to be seen.

The point of the rather limited comparisons made here between heavy-ion theory and the observations that have so far occurred is not to exult in the fits that have been achieved, but rather to emphasize the prospect of settling decisively and quantitatively the uncertainties that abound concerning magnetospheric processes. There are just too many possibilities for adjusting parameters and too many effects that trade off against each other to do this by observation of protons alone. The great sensitivity of many such

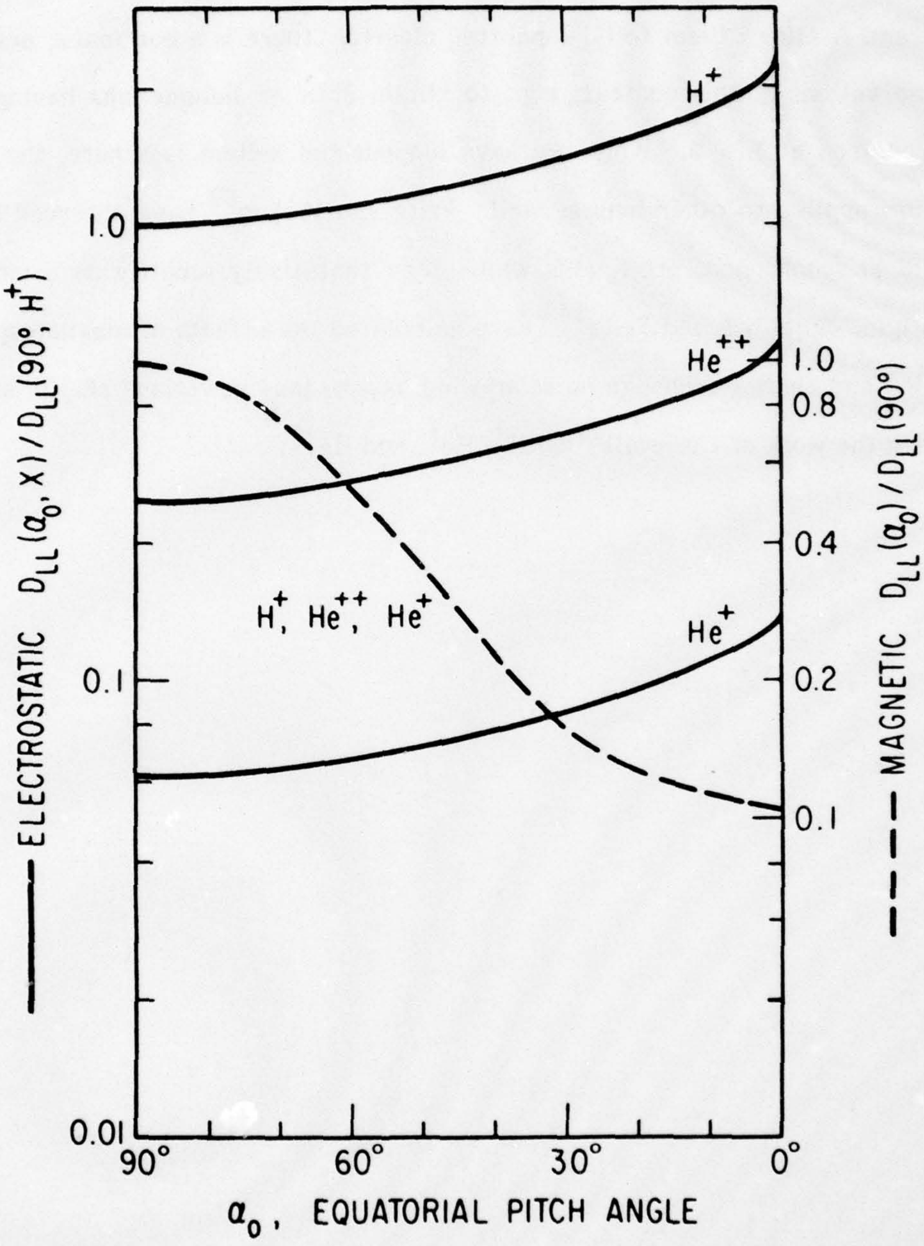


Figure 13. Quantitative representation[57,131] of dependence of radial diffusion coefficients $D_{LL}^{(e)}$ and $D_{LL}^{(m)}$ on equatorial pitch angle and charge state. The relative displacement of right and left ordinates remains to be determined empirically for given E/A and L.

effects to Z and A allows them to be separated clearly. There is a continuing need for improved observations in this context, e.g., to obtain data on helium ions having E/A $\sim$10-15 keV/nucleon at $L > 5$. While we have emphasized helium ions here, the same general picture applies to other ions as well. Fritz and Wilken[63] have observed heavy ions at ATS-6 in synchronous orbit, ions which they tentatively identify as oxygen of solar-wind origin. Spjeldvik and Fritz[149] have calculated the effects of magnetospheric radial diffusion and charge exchange on solar-wind oxygen ions in various charge states, in analogy with the work of Cornwall[35] on H^+, He^+, and He^{++}.

IV. MULTI-ION PLASMA PHYSICS

The presence of several distinct ionic species in a collisionless cold plasma expresses itself by introducing new cutoffs ($n = 0$) and resonances ($n = \infty$) in the refractive index n, as determined by magneto-ionic theory[50,124]. In addition to the expected ion-cyclotron resonances and ion-ion cutoffs for electromagnetic waves propagating parallel to the magnetic field $\underset{\sim}{B}$, one obtains various ion-electron and ion-ion hybrid resonances for oblique propagation[2]. A major historical purpose of magneto-ionic theory has been to study the propagation of radio waves through the ionosphere[124]. Although the proton gyrofrequency falls well below the VLF (very-low-frequency; $\omega/2\pi$ = 3-30 kHz) band at ionospheric altitudes, one may expect to see (ion-electron) hybrid-resonance effects there at VLF. The more exotic ion-ion effects might occur at frequencies below the VLF band, e.g., at 3-3000 Hz (commonly known as the ELF, or extremely-low-frequency, band) or at frequencies $\omega/2\pi \lesssim 3$ Hz (commonly known as the ULF, or ultra-low-frequency, band). Thus, one might expect ionospheric H^+, He^+, and O^+ to affect the downward propagation of ULF communication signals transmitted from the magnetosphere and intended for submarine reception. The same ions might affect the propagation to earth of natural geomagnetic pusations[82] generated in the magnetosphere.

Magneto-ionic resonances ($n = \infty$) and cutoffs ($n = 0$) are often associated with band limits on radio noise observed in space. For example, the VLF receiver aboard the Alouette 1 spacecraft observed emissions that were characterized by a sharply defined lower band limit identified with the lower hybrid resonance[10,24,25,104]. Satellite observations of chorus and ELF similarly show a sharp lower band limit, but this has been identified with a two-ion cutoff in the extraordinary wave mode[72,147]. Observations of VLF electric and magnetic fields with the Injun-5 satellite revealed a host of sharply defined noise bands, both broad and narrow, that were clearly related to several of the various cutoffs and resonances obtained in multicomponent magneto-ionic theory[73]. Such observations yield inferences concerning the relative abundances of various ions in the plasma, since the resonance and cutoff frequencies themselves depend upon the ionic masses and fractional concentrations[11,140].

Notwithstanding the successes noted above, magneto-ionic theory constitutes only one aspect of magnetospheric heavy-ion plasma research. The main thrust in recent years (and for the foreseeable future) has been toward understanding the effects of heavy ions on magnetospheric plasma instabilities. Such effects may or may not entail a <u>resonance</u> between a wave $(\omega, \underset{\sim}{k})$ and a heavy ion. A wave-particle resonance would be characterized by attainment of the condition

$$\omega - k_{\parallel} v_{\parallel} = \ell \Omega_j ; \quad \ell = 0, \ \pm 1, \ \pm 2, \ldots \tag{2}$$

in the case of a nonrelativistic particle of velocity $\underset{\sim}{v}$ and (signed) gyrofrequency $\Omega_j/2\pi$. The subscript j identifies the species and charge state of the ion; the subscript $\parallel$ denotes the projection of the associated vector in the direction of the magnetic field $\underset{\sim}{B}$. The case $\ell = 0$ in (2) is known as the Landau resonance because of its historic role in the theory of damped electrostatic oscillations in an electron plasma[97]. The cases $\ell \neq 0$ correspond to the various orders of cyclotron resonance.

For the case of an electromagnetic wave propagating (i.e., having its $\underset{\sim}{k}$) in the direction of $\underset{\sim}{B}$, only the principal cyclotron resonance ($\ell = \pm 1$, depending on the direction of circular polarization of the wave) is important. For an electrostatic wave with $\underset{\sim}{k}$ parallel to $\underset{\sim}{B}$, only the Landau ($\ell = 0$) resonance is important. The other resonances in (2) occur only for oblique or perpendicular propagation ($\underset{\sim}{k} \times \underset{\sim}{B} \neq \underset{\sim}{0}$). It follows from (2) that there is a certain minimum energy

$$E_\ell^* \equiv m_j v_\parallel^2/2 = (m_j/2k_\parallel^2)(\ell\Omega_j - \omega)^2 \qquad (3)$$

required for a particle of mass m_j to be resonant (in order ℓ) with a wave of frequency $\omega/2\pi$. In the case of a hot plasma there will normally be some such resonant particles for every wave (except that admissible values of ℓ are severely restricted at parallel propagation, as is noted above). In the limit of a cold plasma, resonance can occur only for $\omega = \pm\Omega_j$ or for $k_\parallel = \infty$, i.e., under conditions corresponding to cold-plasma resonances ($n = \infty$) in magneto-ionic theory.

Resonance in the sense of (2) leads to an exchange of energy between the wave and the plasma. In a hot plasma this can lead either to growth (instability) or to damping of the wave. Charged-particle beams and other velocity-space anisotropies are major sources of free energy for producing instabilities, as are gradients in the spatial distribution of plasma[77,78,110]. Plasmas satisfying the Maxwell-Boltzmann distribution are inherently stable and cannot give rise to wave growth, i.e., to an amplification of the energy content of a wave. Gurnett[71] has identified electromagnetic noise bands (in the Hawkeye-1 data) that seem to have arisen through resonant amplification by anisotropic populations of energetic H^+, He^{++}, and heavier ions in the equatorial magnetosphere. Kindel and Kennel[86] have analyzed the conditions for instability of the electrostatic ion-acoustic and ion-cyclotron wave modes in a realistic model of the (multicomponent) topside ionosphere. The free energy in their analysis was provided by a current of precipitating electrons, but resonances between the waves and the heavy ions were essential to the results obtained. In fact, such ion-cyclotron waves have recently been invoked to account for the inferred preferential heating[118] of upward-flowing auroral ions beams[160,161] in the temperature component perpendicular (rather than parallel) to $\underset{\sim}{B}$.

Heavy ions need not be resonant with a wave in order to affect the growth rate. The presence of cold heavy ions (j = h), for example, can affect the value of $k_{\parallel}^2$ belonging to a wave that is resonant only with hot protons, i.e., with j = p in (3). The case of an electromagnetic ion-cyclotron wave with $\underset{\sim}{k}$ parallel to $\underset{\sim}{B}$ yields a spatial growth rate

$$\begin{aligned} -\operatorname{Im} k_{\parallel} \approx\ & (2\pi^2 N_p q_p^2/n^2\omega^2)(2\pi m_p \kappa T_{\parallel}^p)^{-\frac{1}{2}} \\ & \times \left[(T_{\perp}^p/T_{\parallel}^p)(\Omega_p - \omega) - \Omega_p \right] \operatorname{sgn} k_{\parallel} \\ & \times \exp\left[-(m_p c^2/2\kappa T_{\parallel}^p n^2 \omega^2)(\Omega_p - \omega)^2 \right] \qquad (4) \end{aligned}$$

under these circumstances[42], where m_p, q_p, and N_p are the proton mass, charge, and number density, respectively. The proton temperature is assumed anisotropic with respect to $\underset{\sim}{B}$, such that $\kappa T_{\perp}^p > \kappa T_{\parallel}^p$, where κ is Boltzmann's constant. The presence of a cold heavy-ionic constituent (j = h) with its complement of electrons alters $\operatorname{Im} k_{\parallel}$ by changing n^2:

$$\Delta(n^2) \approx (4\pi N_h q_h c/B)(\Omega_h - \omega)^{-1} . \qquad (5)$$

Thus, if the argument of the exponential function in (4) exceeds unity in absolute value[47,48,131], then the addition of cold heavy-ionic plasma will enhance the spatial growth rate[36,42,102] for waves having $\omega < \Omega_h$ but diminish the spatial growth rate for $\omega > \Omega_h$.

It is more difficult than this to estimate the effects of "cold" plasma on electrostatic wave modes, partly because oblique propagation is required in order to generate a situation of physical interest. The search for maximum spatial growth in this case reduces in part to a numerical search for minima in the group velocity $\partial\omega/\partial\underset{\sim}{k}$ and ultimately for nonconvective instability[3,4]. Since the dispersion relation is contingent on plasma temperature here to a greater extent than in the electromagnetic case, it is important not to set $T^j = 0$ for any of the constituents. However, a mixture of hot and "cold" plasmas seems able to produce nonconvective instability where the hot (anisotropic) plasma alone would produce only convective instability. The foregoing comments are abstracted from a study of the effects of hot and "cold" electrons on upper-hybrid waves[3,4]. Similar work has been done recently[5] on the effects of hot and "cold" ions of a single species on the electrostatic ion-cyclotron loss-cone instability[45,76]. This instability should operate outside the plasmasphere, and especially in the auroral region. Since it entails oblique propagation (nonvanishing $k_\parallel$), it is subject to Landau damping by "cold" electrons having thermal velocities comparable to those of the hot ions[5]. Thus, the electrostatic ion-cyclotron instability probably does not operate inside the plasmasphere, where the corresponding electromagnetic instability tends to be enhanced by virtue of (5). In view of the importance of electrostatic cyclotron instabilities outside the plasmasphere, however, it would be of great interest to extend past analyses to the case in which hot and "cold" ions of several species are present simultaneously. Certain aspects of the Post-Rosenbluth electrostatic loss-cone instability[123,127] have been analyzed in this context[37], but much more work remains to be done on this important subject. A brief review of density-sensitive instabilities in general is given by Cornwall[38].

Loss-cone anisotropy is a natural consequence of mirror geometry. However, one does not usually find an otherwise isotropic pitch-angle distribution truncated abruptly at the critical (loss-cone) angle corresponding to particle access to the dense atmosphere. Observed distributions more nearly resemble the bi-Maxwellian form used in (4), insofar as angular distribution is concerned. This configuration would be a natural consequence of pitch-angle diffusion in the presence of a loss cone, since the anisotropy would then be distributed throughout the distribution, which can be decomposed into eigenfunctions that vanish at the edge of the loss cone[126].

Additional sources of anisotropy exist for both light and heavy ions. One of these is radial diffusion at fixed M and J (the first two adiabatic invariants). The fractional energy gain associated with inward transport in L from an external source varies inversely with mirror latitude. Thus, if one examines the equatorial pitch-angle distribution at fixed E and L, the particles with the smaller pitch angles must have originated in the higher-energy (and presumably more impoverished) portions of the source spectrum[116,131]. The other source of ion anisotropy is charge exchange. Charged particles experience a bounce-averaged atmospheric density that increases with mirror latitude[43], and so the particles with the smaller equatorial pitch angles are the most rapidly depleted by charge exchange.

Such anisotropies are subject to limitation by the plasma instabilities that they produce (see above). An electromagnetic proton-cyclotron instability resulting from proton charge exchange has been analyzed by Cornwall[39]. The consequent pitch-angle diffusion leads to a more rapid loss of protons, and to a less rapid growth of proton anisotropy with time, than charge exchange alone would produce during the recovery phase of a magnetic storm. Indeed, such ion-cyclotron waves have been observed at large amplitude ($0.4 - 6.0\gamma$ at 1-30 Hz) in the equatorial magnetosphere ($L \sim 3$-5) in association with enhanced anisotropic ion fluxes on several occasions[153]. However, the combination of proton charge exchange and pitch-angle diffusion ought to produce a more rapid loss of particles than is inferred from the observed decay of the ring current itself, unless the recovery-phase ring current consists mainly of heavier ions such as helium[101,156]. It even seems that charge exchange alone is more than sufficient to account for the observed decay of a ring current assumed to consist entirely of protons and electrons[146]. Helium ions have a smaller charge-exchange cross section for neutralization by the atomic-hydrogen atmosphere at $E \lesssim 50$ keV than do protons[31,34,156]; thus, helium may have become the dominant ring-current constituent by default during the recovery phase (see Figure 10, in Secton III).

The prospect of a helium-dominated ring current during recovery phase at $E \lesssim 50$ keV certainly requires a new analysis of the ion-cyclotron instabilities that might occur. During the transition from hydrogen dominance to helium dominance, for example, one must take account of both ionic species in the hot-plasma dispersion relation. Moreover, the resulting ion-cyclotron waves can serve as a medium for energy exchange between the ionic species. The cited argument[101] for a helium-dominated recovery phase ring current ignores the role of radial diffusion, which presumably persists even while the ring current is decaying. However, radial diffusion seems to favor proton dominance only for drift periods $\ll$ 2 hr, i.e., for $E \gg 30(Z/L)$ keV (see Figure 12 in Section III). It follows from (1) that D_{LL} is substantially independent of species for ring-current energies ($E \lesssim 50$ keV) that are of interest in the present context[35]. Observations of precipitating ions during recovery phase[139] have revealed little helium but much hydrogen and oxygen. Direct observations of the equatorial ring current with ion-identifying spectrometers are not yet available. However, the question of helium dominance during recovery phase might well be resolved[14] by examining the spectrum of equatorial ions observed[80,111,114,129] at very low altitudes, earthward of the inner zone. These ions form a partial radiation belt that is fed by the stripping of energetic neutral atoms that were created at high altitudes ($\gtrsim$ 20000 km) by the charge exchange of ring-current ions. Identification of species is made possible by the fact that the product of cross sections for the two steps in the process depends much differently on energy for the two major ring-current ions[14].

When considering the effects of heavy ions on plasma instabilities, one should not discount the effects of the same instabilities on the heavy ions themselves. Cladis[30], for example, points out that electromagnetic proton-cyclotron waves destabilized by magnetospheric proton anisotropy may energize ambient oxygen ions at low altitudes. He invokes the phase-trapping of particles by such waves in the inhomogeneous medium to account for energization beyond that possible in quasilinear theory. This is reminiscent of an analogous mechanism proposed by Swift[150] for electron energization by downward-propagating electrostatic waves, a mechanism that has since been investigated numerically[66] and analytically[98]. Brice and Lucas[22] have described the heating of natural helium and oxygen ions (and of artifically injected lithium ions) in the ring current as a natural consequence of instability enhancements. Moreover, the enhancement of such instabilities may lead to the nonlinear coupling of large-amplitude waves, $(\omega_1, \underset{\sim}{k}_1)$ and $(\omega_2, \underset{\sim}{k}_2)$, to produce disturbances at $(\omega_1 \pm \omega_2, \underset{\sim}{k}_1 \pm \underset{\sim}{k}_2)$ that may interact resonantly with portions of the particle distribution that would have been accessible to neither wave in the linear theory[20,22]. Various quasilinear and nonlinear aspects of the mechanism[41] whereby unstable electromagnetic proton-cyclotron waves heat ambient electrons, which conduct their added energy down the field line and thereby excite atomic oxygen to produce a SAR-arc (see Section I), have been discussed by Galeev[65].

In concluding this long section on heavy-ion plasma physics, we digress to make a more general remark about space plasma physics. To an outside observer it often seems that plasma theorists concoct a plasma instability to account for every observation, and that we search for an observation to support every instability that theory predicts. There is some truth in this accusation. Perhaps the role of plasma instabilities as such is overstated. Let us consider what the consequence of a plasma instability might be: a spectrum of turbulent fluctuations that can interact with the distribution of charged particles. On the other hand, what can be said of a stable plasma containing substantial free energy? One can say that it is characterized by a spectrum of fluctuations that interact with the distribution of charged particles, a spectrum that becomes more and more intense as the parameters of the system are adjusted toward a state of marginal instability[155]. In terms of the physical consequences, there is a continuous transition between stability and instability. Only the mathematical description is dichotomous. Let us proceed with ths perspective in mind.

V. ACTIVE PLASMA-INJECTION EXPERIMENTS

As has been discussed in the previous section, a magnetospheric plasma that contains more than one ionic species in substantial abundance may have quite different properties from a plasma without the heavy ions. These differences extend to both wave-propagation and instability characteristics. Some of the properties, usually those concerning emission at the very lowest frequencies ($\omega \ll \Omega_p$), depend strongly on the species of the heavy ion that is present. Other properties, notably those that affect analogous electron emissions (see below), depend mostly on the total charge density of the added ions. All active experiments presently contemplated depend on photo-ionization to make plasma from injected neutral particles; thus, the only substances that are useful in this context are those having photo-ionization times $\lesssim 1$ hr in sunlight. Hydrogen is excluded by this consideration, but barium, cesium, lithium, and perhaps a few other substances are practical for artificial plasma injection.

The use of artificial plasma injection as a technique for enhancing magnetospheric plasma instabilities was first proposed by Brice[18,19] in the context of whistler-mode (electron-cyclotron) waves. The whistler-mode instability seems to be driven[85] by an electron-temperature anisotropy ($T_\perp^e > T_\parallel^e$), and the spatial growth rate ($-\mathrm{Im}\, k_\parallel$) is that given by analogy with (4):

$$
\begin{aligned}
-\mathrm{Im}\, k_\parallel \approx\ & (2\pi^2 N_e q_e^2/n^2\omega^2)(2\pi\, m_e \kappa T_\parallel^e)^{-\frac{1}{2}} \\
& \times \left[(T_\perp^e/T_\parallel^e)(|\Omega_e| - \omega) - |\Omega_e| \right] \operatorname{sgn} k_\parallel \\
& \times \exp\left[-(m_e c^2/2\kappa T_\parallel^e n^2 \omega^2)(|\Omega_e| - \omega)^2 \right], \qquad (6)
\end{aligned}
$$

where the subscript e refers to the hot electrons. The presence of a cold heavy-ionic plasma constituent (j = h) with its complement of cold electrons[21] would alter Im $k_\parallel$ in (6) by changing n^2:

$$\Delta(n^2) \approx (4\pi N_h q_h/m_e)(|\Omega_e| - \omega)^{-1}(\omega + \Omega_h)^{-1}|q_e|. \qquad (7)$$

Thus, the enhancement of $-\mathrm{Im}\, k_\parallel$ via $\Delta(n^2)$ is independent of ionic species for $\Omega_h \ll \omega < [1 - (T_\parallel^e/T_\perp^e)]|\Omega_e|$ and contingent only upon the charge density $N_h q_h$, provided that the argument of the exponential in (6) exceeds unity in absolute value[49].

The amount of plasma needed to conduct an active experiment is not large. Typical barium releases inject a fraction of a kilogram of Ba, which is photo-ionized in ~20 sec. At an expansion velocity ~1 km/sec, an ionospheric plasma cloud would thus attain a nominal radius ~20 km across $\underset{\sim}{B}$, but it might ultimately attain a length $\gtrsim 10^3$ km along $\underset{\sim}{B}$. Half a kilogram of Ba^+ would fill this volume to a density ~2000 cm^{-3}, and even higher densities would have been attained before the barium cloud reached its full length. There are three methods of Ba^+ injection: (1) rocket-borne canisters of barium exploded in the ionosphere to produce a cloud that is initially isotropic and confined to the ionosphere[74,75,169]; rocket-borne shaped-charge releases, which create a cloud that can extend along an entire field line[165-168]; and (3) high-altitude releases in the magnetosphere[75]. There is a great difference between the physics of ionospheric Ba^+ releases and the physics of high-altitude releases. Ionospheric release yields a low value ($\ll 1$) for β, which is defined as the ratio of plasma pressure to $B^2/8\pi$. In this case there is only a minimal distortion of the earth's local magnetic field $\underset{\sim}{B}$. There may or may not be a major distortion of the local electric convection field $\underset{\sim}{\mathcal{E}}$.

This would depend on the resistance of the electric circuit that links the plasma cloud with the ionosphere. If there is no major distortion of $\mathcal{E}$, then the barium cloud drifts[74] with the ambient convection velocity $(c/B^2)\ \mathcal{E} \times B$. Moreover, there occur drift-wave instabilities that lead to an easily observed striation of the plasma cloud[100,164] in the presence of collisions between the Ba^+ ions and the neutral atmosphere. A barium release at high altitude (e.g., several earth radii out in the magnetosphere) does not entail collisions between the Ba^+ ions and the neutral atmosphere, but it does entail a high-beta ($\beta \gg 1$) condition. The result is a severe distortion of the local B field, such that both B and $\mathcal{E}$ are initially excluded from the expanding plasma cloud, which is highly conducting. Eventually the earth's magnetic field diffuses back into the plasma cloud and the electric convection field penetrates the cloud as well. Meanwhile, the cloud has transferred its excess momentum (over that which it would have contained if traveling at the convection velocity) to the ambient plasma. For plasma clouds such as those released from HEOS 1 at an altitude ~70000 km, however, this transfer takes place on a time scale of hours[75]. Scholer[128] and Pilipp[122] have discussed the motion to be expected from such magnetospheric barium releases.

It has not been possible so far to draw any definite conclusions about the influence of such high-altitude releases on the magnetosphere itself. The barium clouds have such small transverse dimensions that it is difficult to locate (by remote means) the tiny volume of magnetosphere that would be affected. (However, Wescott et al.[166] have discussed a substorm that may possibly have been triggered by a shaped-charge barium release.) On the other hand, there is some evidence for increased wave emission and increased energetic-electron flux following ionospheric barium releases, which often find the instrumented rocket in the middle of the plasma cloud. Such effects have been reported by Kelley et al.[84] and by Köhn and Page[89]; the effects were too complex to be described in detail here. More recently, Koons and Pongratz[90] have reported the direct excitation of electrostatic ion-cyclotron waves, in the ambient ionospheric plasma as well as in the artificially injected plasma, by the impulse associated with a shaped-charge Ba release at 450 km altitude.

Although it is very much worthwhile to continue experiments that involve the release of barium, one should recognize that barium has certain limitations for use in magnetospheric research. The small transverse dimension has been noted above, together with the high-β conditions that this often implies. Moreover, barium plasma is unsuitable for experiments designed to enhance electromagnetic ion-cyclotron instabilities by means of (5). To create a meaningful enhancement of $-\,\mathrm{Im}\,k_{\parallel}$, one would wish to inject cold plasma outside the plasmasphere (where there is little, if any, cold plasma of natural origin) but near the equator (where the hot plasma is concentrated by virtue of the inequality $T_{\perp}^{P}/T_{\parallel}^{P} > 1$). The Ba^{+} gyrofrequency can hardly exceed 0.05 Hz there, and only waves below this frequency can have their growth rates enhanced by the addition of cold plasma[42]. Except perhaps within the barium cloud itself, the wavelength corresponding to such a low frequency will likely exceed the diameter of the magnetosphere. It is difficult to imagine observing such a "wave" at all, not to mention its "enhanced" instability. Moreoever, the growth rate at such low frequencies is very small compared to the maximum that occurs at $\omega = [1 - (T_{\parallel}^{P}/T_{\perp}^{P})]\epsilon\Omega_{p}$ in the absence of cold plasma[42,102], where $0.8 \lesssim \epsilon < 1$ if $\beta \lesssim 1$. Thus, the addition of cold barium plasma to the magnetosphere may well enhance electron-cyclotron instabilities via (7), but would tend to suppress the ion-cyclotron instabilities that are (in some respects) more interesting. The same objection holds in the case of cesium.

As for lighter ions, the only parent neutral with a reasonably short photoionization lifetime (~ 1 hr) is lithium, which has repeatedly been released into the ionosphere over the years, both from rockets and through thermonuclear explosions. Neutral Li is readily observed as a resonant scatterer of sunlight, but the Li^+ ion is completely invisible. Lithium clouds injected from rockets launched at twilight have been observed with brightnesses in the kilorayleigh range; 1 kR corresponds to 10^9 photon emissions per second by the atoms contained in a column whose cross section (measured in the plane transverse to the line of sight) is 1 cm^2.

It has been proposed (but not yet attempted) to make large-scale lithium releases near the equator outside the plasmasphere as a means of triggering electromagnetic instabilities driven by ring-current ions. The naturally occurring plasma there is of low density (often $< 1\ cm^{-3}$), and it is technologically feasible to add lithium plasma at a density $> 1\ cm^{-3}$ over a large region of space (see below). Readily observed effects should occur at Li^+ densities much more modest than $1\ cm^{-3}$, but the enhancement of $-\mathrm{Im}\, k_\parallel$ occurs only below the lithium gyrofrequency ($\omega \approx 0.14\,\Omega_p$) rather than at the growth-rate peak in the absence of lithium ($\omega \sim 0.4\,\Omega_p$ for $T_\perp^p \sim 2T_\parallel^p$ and $\beta \sim 1$). For example, Figure 14 shows the effect of a 10% increase in the plasma number density[102] on the temporal growth rate $\gamma \equiv -(d\omega/dk_\parallel)\,\mathrm{Im}\, k_\parallel$ when Li^+ is added to an already unstable hot hydrogenic plasma having $T_\perp^p = 2T_\parallel^p$ and $\beta_\parallel^p \equiv 8\pi N_p \kappa T_\parallel^p/B^2 = 1$. The result is a narrow band of emissions just below the Li^+ gyrofrequency, where there had been none before. However, the growth rate for this band remains much smaller than the peak γ in the absence of Li^+, and one would need considerably more than 10% lithium plasma (by number density) to make the peak at

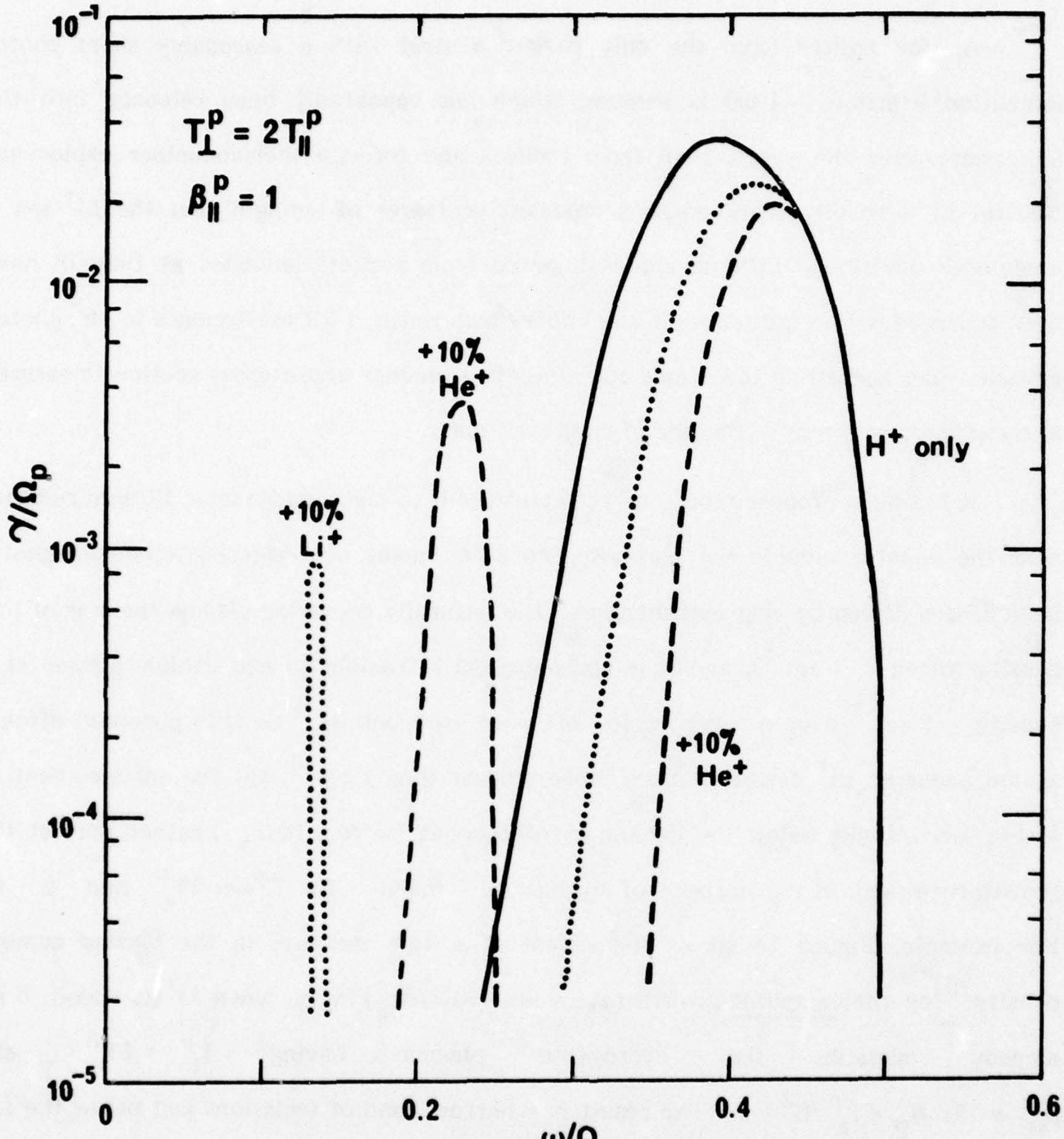


Figure 14. Normalized temporal growth rates[131] for electromagnetic ion-cyclotron waves in plasmas consisting of hot protons, cold electrons, and (in two cases) additional cold plasma at 10% of proton number density, as calculated by Mark[102].

$\omega \approx 0.14\,\Omega_p$ dominant over that at $\omega \sim 0.4\,\Omega_p$. *These considerations have led* Mark[102] to advise against adding lithium to an already unstable hydrogenic plasma outside the plasmasphere. Of course, if the hot ions were helium (He^+), the naturally occurring emissions would peak at $\omega \sim 0.1\,\Omega_p$ and the addition of even small amounts of lithium would enhance this peak. However, the arguments cited in Section IV for a helium-dominated ring current are contingent on charge exchange, which decreases in *importance with increasing* L, and are addressed specifically to the recovery phase of a magnetic storm. One cannot rely on the ring current to be helium-dominated at all times and in all places. Far more dramatic would be the effect of adding lithium to a stable hydrogenic plasma (e.g., having $T_\perp^P \lesssim 1.2T_\parallel^P$ with $\beta_\parallel^P \sim 1$). In this case the peak value of $-\mathrm{Im}\,k_\parallel$ (which probably would occur at $\omega \lesssim 0.14\,\Omega_p$) is likely to be insufficient (in the absence of cold plasma) to overcome the losses that occur at the ends of the amplification path. The addition of even a modest density of cold Li^+ should enhance this peak value of $-\mathrm{Im}\,k_\parallel$ enough to overcome such losses; a plasma having roughly equal number densities of cold Li^+ and hot H^+ has been found to be unstable for anisotropies that were quite small[42].

Because neutral lithium has a photoionization time ~ 1 hr and a larger thermal velocity than similarly injected barium, it should attain a radius $\sim 10^4$ km transverse to $\mathbf{B}$. *A spherical cloud of this radius would require* ~ 150 kg of Li^+ to reach a uniform density $\sim 3\ \mathrm{cm}^{-3}$. Such a cloud, however, would envelop $\sim 10^{20}$ erg (roughly equivalent to 2.4 kilotons of TNT) in the form of geomagnetically trapped (particle) radiation, some fraction of which might well be released in the form of waves, precipitating particles, and various substorm-like manifestations of the expected plasma instabilities if the experiment were conducted.

In fact, injections of ions lighter than barium have undoubtedly occurred already near synchronous altitude ($\sim$35000 km), when rocket engines were burned to maneuver a satellite into the desired circular orbit. Paulikas[119] has looked for effects associated with such injections and found none, but probably because the plasma clouds were too small. Kivelson and Russell[88] have looked, with considerable success, for such effects associated with the "injections" of cold hydrogen plasma that occur naturally during sporadic erosions of the plasmasphere that are associated with changes in the electric convection field. Moreoever, Kintner and Gurnett[87] have identified from their Hawkeye-1 data several episodes of electromagnetic proton-cyclotron wave occurrence near the plasmapause, often just inside the plasmasphere.

In some respects it is unfortunate that the controlled injection of H^+ plasma into the magnetosphere by conventional means is an impossible experiment. Much of the motivation for active plasma-injection experiments is to simulate the effects of naturally occuring regions of high-density magnetospheric plasma. It was originally suggested by Cocke and Cornwall[33] that the electromagnetic proton-cyclotron mode could be made unstable by a high density of cold plasma in the magnetosphere. This picture later developed into a theory of storm-time dynamics[40] and of SAR-arc generation[41]. Some results[172,173] from S^3 (Explorer 45) strongly suggest that the equatorial proton ring current ($E \sim$ 1-200 keV) interacts with the plasmasphere in essentially the manner predicted by the theory, although detailed information on electromagnetic cyclotron waves at the equator is sparse[154]. For example, Williams and Lyons[172] have reconstructed a hypothetical plasma-density profile at the plasmapause from their particle data by invoking (3) at marginal stability for $\ell = 1$. It follows from (4) that Im $k_{\parallel} = 0$ for

$$\omega = \omega^* \equiv \left[1 - (T_\parallel^p / T_\perp^p)\right] \Omega_p \,. \tag{8}$$

The refractive index n at $\omega = \omega^*$ can be calculated[42] as if in a cold plasma ($\beta \ll 1$). Thus, one obtains (for $\omega = \omega^*$) the fact that

$$n^2 \equiv (ck_\parallel / \omega)^2 = 1 + \left[1 - (\omega / \Omega_p)\right]^{-1} (c/c_A)^2 \,, \tag{9}$$

where c_A is the Alfvén speed, and from (3) the result (assuming $n^2 \gg 1$) that

$$E_1^* \approx (m_p c_A^2/2)\left[(T_\perp^p / T_\parallel^p) - 1\right]^{-2} (T_\parallel^p / T_\perp^p)$$

$$\approx (B^2/8\pi \overline{N}_p)\left[(T_\perp^p / T_\parallel^p) - 1\right]^{-2} (T_\parallel^p / T_\perp^p) \,, \tag{10}$$

where $\overline{N}_p$ is the total density of hot and cold protons (or their mass-equivalent) in the equatorial plasma. By identifying the critical energy that corresponds to a marked change in the pitch-angle distribution at a given L value, Williams and Lyons[172] obtained the equatorial density profile $\overline{N}_p = (B_o^2/8\pi E_1^*)$ shown in Figure 15, where we have eliminated the arbitrary dependence on $T_\perp^p / T_\parallel^p$ in (10) by assuming $T_\perp^p \approx 1.755\, T_\parallel^p$ (this being reasonable, if not self-consistent). The vertical bar represents an independent measure of $\overline{N}_p$ from saturation of the on-board DC electric-field probe. This agrees well with the profile $\overline{N}_p = (B_o^2/8\pi E_1^*)$, which, moreover, has the expected shape.

The early ideas of Brice[18,19] have thus undergone considerable elaboration and refinement[36,42,47-49,102] during the past several years, but his proposal to seed the magnetosphere with cold plasma to simulate naturally occurring substorm effects

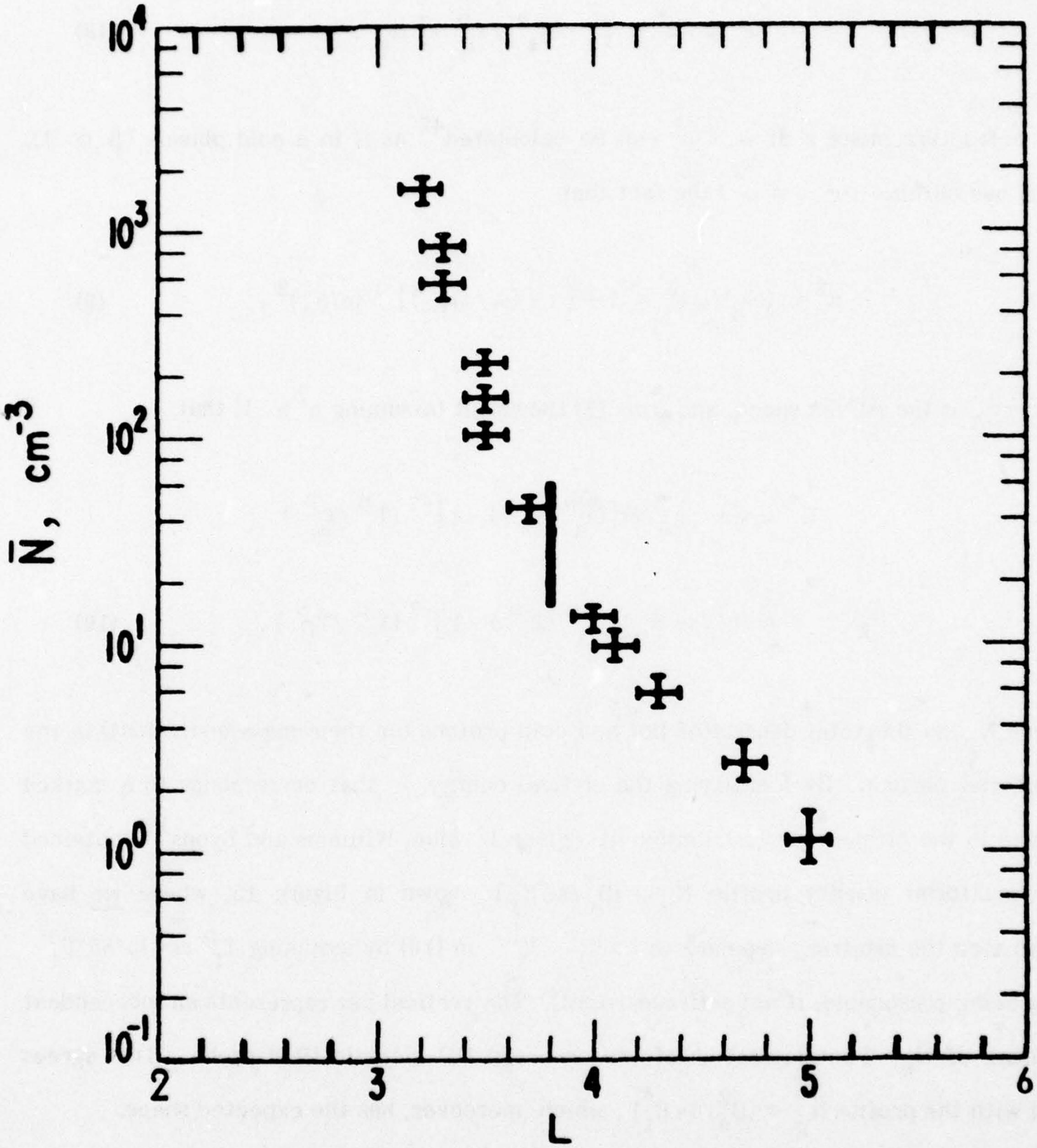


Figure 15. Plasma densities $N \sim (B_o{}^2/8\pi E_1^*)$ inferred by Williams and Lyons[172] from energy E_1^* $\sec^2\alpha_o$ characteristic of transition from anisotropic to nearly isotropic equatorial pitch-angle distribution at Explorer 45 (S^3). Vertical bar denotes independent density estimate based on observed saturation of on-board DC electric-field probe.

remains as attractive as ever. Brice did not specifically take into account the damping effect of cold heavy ions on proton-driven waves, and he used the concept of a maximal stably trapped flux[85] rather uncritically to predict the triggering of large-scale precipitation of energetic particles upon the injection of cold plasma into the magnetosphere. The difficulty of destabilizing proton-driven instabilities is partially overcome by using lithium in place of barium or cesium for the experiment[36,42]. Use of lithium rather than hydrogen makes it impossible to simulate naturally occurring phenomena exactly, but lithium has its own advantages. For a given number density of ions, lithium is seven times as effective as H^+ in lowering the parameter c_A^2 in (10), and thus in lowering E_1^*. Moreover, as has been noted above, lithium is an especially appropriate additive when the proton anisotropy is small, e.g., when $T_\perp^P \lesssim 1.25\, T_\parallel^P$. In this case the peak growth rate in the absence of cold plasma might well have occurred at or below the lithium gyrofrequency, a condition that would overcome the objection raised by Mark[102] against the injection of Li^+ into a significantly more anisotropic ($T_\perp^P \gtrsim 2T_\parallel^P$) proton ring current. The performance of active experiments in space has a bright future, and lithium-plasma injection into the magnetosphere should play an important role in that future. This subject will be addressed again in Section VII.

VI. HEAVY-ION PHYSICS AT JUPITER

Needless to say, the study of heavy-ion physics in other planetary magnetospheres is even less advanced than it is in the earth's. In a recent 1200-page comprehensive review of Jupiter[67], for example, there are no articles specifically addressed to the Jovian analogue of any of the previous sections of the present paper. Some results on energetic alpha particles from the Pioneer-10 data[145,158] have been reported outside that review. For energies of several MeV/nucleon the α/p flux ratio was found to range from 10^{-3} to 10^{-2} along the roughly equatorial orbit, but nothing is known about the α/p ratio at lower energies.

The possible physical mechanisms that might involve Jovian heavy ions are more elaborate than the mechanisms that operate in the earth's magnetosphere. In addition to ionospheric and solar-wind sources, one must consider ions derived from Jupiter's major satellites, which orbit well inside the magnetosphere. Many more ionic species are involved at Jupiter than at the earth, and some of these (e.g., the ions of He, C, O, Ne, Na, Mg, S, and Fe) can be used for distinguishing sources, acceleration mechanisms, and transport processes. Neutral sodium has been observed[26,157] around the orbit of Jupiter's satellite Io, as well as ionized sulfur[96,109]. The clouds of Na and S^+ appear to form a partial torus that extends eastward and westward from Io and encircles the planet[53,107,108], thus filling a significant region of Jupiter's magnetosphere. (Ionized sodium and neutral sulfur would not be observable by earth-based spectroscopy.) No other heavy ion has been definitely identified in the Jovian magnetosphere. The other ions listed above are expected on the basis of models of the composition of Jupiter and its Galilean satellites. Io is also known to have a cloud of neutral hydrogen[28] which forms a partial torus, and Ganymede (which is known to consist largely of H_2O) might theoretically have a similar corona. Such clouds of neutral hydrogen could play an important role in removing heavy ions by charge exchange, just as in the earth's magnetosphere. Aside from the satellites, there are essentially no known sources for low-energy neutrals in the Jovian magnetosphere.

One outstanding feature of Jupiter is the rapid rotation rate that it transmits to the magnetosphere, seemingly at least to the orbit of Ganymede ($r \approx 15r_J$). Indeed, at particle energies $\lesssim$ 8 MeV/charge the contribution to the drift rate from gradient-curvature effects is smaller than the corotation rate for $L \lesssim 15$. Particles having $E/Z \ll 8$ MeV/charge all have essentially the same drift frequency and (therefore) the sam radial-diffusion coefficient D_{LL}, regardless of Z or A; tests discussed in Section III to identify the radial-diffusion process are inapplicable at Jupiter because of this

degeneracy. Actually, the radial-diffusion processes represented by (1) are believed to be less important at Jupiter than that caused by the fluctuating electric polarization fields associated with variable neutral winds in Jupiter's ionosphere[23,44].

The rapid corotation of Jupiter's magnetosphere drags magnetospheric plasma and zenomagnetically trapped radiation past the Galilean satellites so as to produce several possible effects: (1) impact of corotating energetic particles on a satellite may liberate atoms or ions into the magnetosphere; (2) corotation-induced electrostatic fields may accelerate thermal plasma (along $\underset{\sim}{B}$) up to several hundred keV at Io, or up to 90 keV at Ganymede, enabling these particles to liberate atoms or ions from the surface; and (3) magnetospheric ions may be lost not only through direct impact[106] on a satellite, but also by charge exchange as they drift through the satellite's corona of neutral atoms.

Admittedly little is known about the rates at which ions or atoms can be sputtered from a satellite surface by a given incident particle flux, and the magnitude of the incident particle flux itself is highly uncertain. It has been pointed out[132] that if Io is a good electrical conductor, as Piddington and Drake[121] have proposed, then Io's effective cross section for impact by magnetospheric particles may be very different from Io's geometric cross section. Its swath is found to be enhanced (over the geometric value) for electrons having $E \gtrsim 30$ MeV. A similar effect should obtain for a satellite, such a Ganymede (see above), that is a good dielectric (in this case consisting mostly of water).

Charge-exchange processes have implications for remote sensing of satellite coronas as well as for magnetospheric dynamics. A simple measure of the effectiveness of charge exchange in removing ions is the product $N \sigma v \tau$, where N is the average number density of neutral atoms in the corona, τ is the amount of time that the energetic ion spends in this neutral cloud, and σ is the charge-exchange cross section at relative ion-neutral velocity $\underset{\sim}{v}$ (which is essentially the ion velocity associated with the gyro and bounce motion). For 50-keV protons incident on atomic hydrogen (see Figure 10) one obtains $\sigma v \approx 3 \times 10^{-8}$ cm^3/sec; for He^{++} at the same energy one obtains $\sigma v \approx 1.5 \times 10^{-7}$ cm^{3}sec. A magnetospheric ion might require $\tau \sim 2$—100×10^6 sec to diffuse across a neutral cloud of minor diameter $2r_J$ at Ganymede ($L = 15$) and perhaps 15—200 times as long through a similar cloud at Io ($L = 6$). The uncertainty in these time estimates reflects to some extent the uncertainty in the mechanism primarily responsible for D_{LL}. The lower estimates here correspond to the Brice-McDonough[23] mechanism (ionospheric neutral winds) with a recommended[44] coefficient $D_{LL} \sim 2.3 \times 10^{-10} L^3$ sec^{-1}. Significant charge exchange of H^+ would have occurred in the interim if $N \gtrsim 1/\sigma v \tau$, i.e., if $N \gtrsim 1$ cm^{-3} around Io's orbit or if $N \gtrsim 15$ cm^{-3} around

Ganymede's. Carlson and Judge[28] report a column content $\sim 3 \times 10^{12}$ cm^{-2} for neutral hydrogen, based on Lyman-α measurements from Pioneer 10. This would correspond to a number density $N \sim 200$ cm^{-3} if the cloud had a diameter comparable to that of Jupiter itself. The product $\sigma v \tau$ decreases drastically with increasing energy, but significant charge-exchange effects might still occur for energies up to several hundred keV at Ganymede and several MeV at Io.

For lack of space, we do not analyze other possible injection, loss, and acceleration mechanisms for heavy Jovian ions; these would be analogous to mechanisms that operate in the earth's magnetosphere. It might be difficult to distinguish between solar-wind and ionospheric sources for trapped Jovian radiation, since Jupiter's atmosphere should have a composition rather like that of the photosphere. An interesting exception to this generalization is the CNO group, whose atoms are presumably tied up in chemical compounds (e.g., H_2O, NH_3, CH_4, C_2H_2) in Jupiter's atmosphere and have low elemental abundances there. Apart from the case of acetylene (C_2H_2), however, it might be difficult to distinguish the ionized atom from the ionized molecule in terms of mass or charge.

An additional note concerning sulfur and sodium seems in order. These seem to occur in a torus surrounding the orbit of Io. Strangely enough, sodium and sulfur do not seem to co-exist in the torus[26,96,109,157]. Either one or the other seems to be present at any given time, but not both. It has been suggested[52] that the transition from a sulfur torus to a sodium torus might be accompanied by a magnetohydrodynamic (MHD) transformation in Jupiter's magnetosphere, i.e., that Jupiter's magnetosphere is like the sun's (with strong radial outflow of plasma) in the sulfur phase and like the earth's (with only a weak polar wind at best) in the sodium phase. Changes in the Alfvén speed c_A

relative to the equatorial corotation velocity (13L km/sec) might account for such an MHD transformation[52].

Finally, we should mention that the study of Jupiter's magnetosphere teaches important lessons about the earth's. It has been noted[130] that the radial-diffusion coefficient $D_{\Phi\Phi}$, corresponding to electrostatic and/or magnetic impulses of the sort described by (1), should vary at least as the fifth power of the earth's dipole moment M_e, where Φ is the third adiabatic invariant. (One speaks here of $D_{\Phi\Phi}$ rather than D_{LL} because L is not an adiabatic invariant unless M_e is constant in time.) One expects the Brice-McDonough[23] $D_{\Phi\Phi}$ to have a weaker variation with M_e, perhaps becoming the dominant radial-diffusion mechanism in the earth's magnetosphere at epochs of unusually small M_e (e.g., about 6000 years ago, when M_e amounted to $\leq 50\%$ of its present value). Thus, a diffusion mechanism that was initially contemplated in response to a puzzle presented by Jupiter may turn out after all to have played an essential role in the ancient history of the earth.

VII. THE FUTURE OF MAGNETOSPHERIC HEAVY-ION PHYSICS

There are three vital observational aspects of magnetospheric heavy-ion physics that remain unexplored to this day: (1) as was mentioned in Section I, there is an instrumentation gap for ions between ~ 20 keV/charge and ~ 200 keV/nucleon, and no direct charge-composition measurements are available in this range; (2) satellites instrumented for low-energy ion-composition measurements have not traversed the region $5 \lesssim L \lesssim 10$ near the equator, a region of special significance in view of the very sharply peaked pitch-angle distributions of protons and (especially) alpha particles that are observed near the equator at lower L values; and (3), there is very little information available about the distribution of heavy ions in the magnetospheres of other planets. A number of recent proposals to fill these observational gaps will be discussed below.

Several of the barium-injection experiments[74,75,165,169] cited in Section V were essentially passive in that they were designed to trace magnetic field lines or to monitor drift at the ambient electric convection velocity $(c/B^2)\,\boldsymbol{\mathcal{E}} \times \mathbf{B}$. More experiments of this type are planned for the future. Several other past experiments have had the effect of modifying localized regions of the magnetosphere[75,84,89,90], and at least one[166] may have triggered a large-scale magnetospheric response. Much less work has been done, however, with unequivocally active plasma injection experiments designed to modify a large region of the magnetosphere. While some of the proposed experiments are undoubtedly too expensive, it nevertheless seems quite worthwhile to develop at least a modest program for large-scale active plasma releases in the magnetosphere.

There is, of course, no abrupt transition from the heavy-ion physics of the past to that of the future. At this writing the Voyager spacecraft approaches Jupiter with

E·dE/dx telescopes, the first International Sun-Earth Explorer (ISEE) has just been launched with an ion-composition instrument (E·dE/dx telescope plus TOFD: see Section I), and the GEOS satellite (with ESA's) had preceded ISEE. These satellites undoubtedly will provide much new and useful data. Unfortunately, the orbits of the earth satellites are not ideal: although they reach high L values, the satellites do not remain near the equator for any significant fraction of the time. Nor do they fill in the instrument gap mentioned above and in Section I.

A number of groups have proposed to fill most of the instrument gap; a typical solution is that proposed by Gloeckler[68]: Incoming ions are collimated, and those of a given energy/charge are selected by an electrostatic-deflection analyzer. These ions pass through a TOFD and are stopped in a detector that measures their total energy. Energy, mass, and charge can thus be measured from very low energies up to about 400 keV/charge. The instrument is capable of isotopic separation for elements as heavy as carbon and elemental separation up to iron. The upper energy limit is set by the size of the TOFD and electrostatic-deflection system. An instrument of this type will virtually double our knowledge about low-energy helium ions in the magnetosphere by separating He^{+} from He^{++}. We recall from Section III that such information is vital in assessing the balance between radial-diffusion and charge-exchange processes. An unavoidable drawback of the above instrument is its rather modest upper energy limit. No one has suggested a way of measuring charge states at $E/A > 1$ MeV/nucleon with instruments of reasonable size, and so this part of the instrument gap remains.

A proposal to use an instrument of the above type in a satellite that has an equatorial orbit and and ranges over $2 \lesssim L \lesssim 10$ is under consideration by NASA as part of the OPEN (Origins of Plasma in the Earth's Neighborhood) program. The other part of the program calls for an investigation into the composition of the interplanetary plasma and energetic particle population by constituents. It is not clear that the two missions are compatible on a single satellite, since the orbit required for the interplanetary phase would (like ISEE's orbit) be unsuited for the magnetospheric phase of the mission. With a well chosen orbit, however, the OPEN program should have high priority as a magnetospheric mission.

A wide variety of active and passive plasma-injection experiments could be performed on Space Shuttle flights during the 1980's. The low altitude of the Space Shuttle orbit will necessitate use of shaped charges or Shuttle-launched satellites to inject plasma all the way to the equator, but it should be possible to inject many tens of kilograms of ions into that portion of the magnetosphere that lies outside the plasmasphere, into the dayside cleft, or into other interesting regions. A general picture of what can be accomplished in this context has already been discussed in Sections III and V.

As a first step in this direction, the AMPTE (Active Magnetospheric Particle Tracer Experiment) program calls for injection and tracing of plasma with two conventional satellites: one for injecting the plasma and one for tracing it. Injection would occur not only in the magnetospheric tail but also in the solar wind near the nose of the magnetosphere, using lithium and perhaps europium. The tracer satellite is proposed to have an equatorial orbit with apogee reaching at least to L = 8. It would carry a set of composition detectors that fill the instrument gap mentioned above and in Section I. The tracer satellite is therefore similar to the OPEN satellite; either could be used to study the injected ions.

There is an obvious reason for using tracer ions such as lithium and europium which do not occur naturally in the magnetosphere: they are analogous to the red dye injected into water in a hydrodynamic-flow experiment. As long as one is interested only in studying convective transport, there is no difficulty. However, once these ions acquire enough energy that diffusion outweighs convection, they may not be transported as rapidly as protons of the same E/A and will not directly reveal what happens to protons. Of course, such heavy ions will be extremely important as <u>indirect</u> probes of the mechanism responsible for radial diffusion in general (and of protons in particular) when taken in conjunction with the theoretical framework outlined in Section III. Such radial-diffusion studies are quite readily done with naturally occurring ions in the magnetosphere. The real value of exotic ion tracers is to study particle injection into the magnetosphere: to determine what percentage of the ions from a given location in the solar wind or geomagnetic trail ultimately enter the region of trapped particles, where they enter it, what might be the relationship of the plasma sheet to the radiation belts, and so on.

The last observational topic on our agenda relates to ion-composition studies in other planetary magnetospheres, notably that of Jupiter. To study the Jovian magnetosphere from a satellite in Jovian orbit is a high-priority goal of the near future; it has been combined with an entry probe into Jupiter's atmosphere in the Jupiter Orbiter Probe (JOP) program. The Orbiter should be capable of studying the magnetosphere for a long period of time. This will require an orbit at $r \gtrsim 15r_J$ if the vehicle is to avoid severe radiation damage to its instruments. Fortunately, the satellite Ganymede has an orbital radius of about $15r_J$, a coincidence that will enable the Orbiter to conduct detailed studies of this largest Jovian satellite and its interaction with Jupiter's radiation belts. Unfortunately, direct studies of Io and Europa would not be possible unless the Orbiter were sent into a much lower orbit near the end of the mission. The Probe would report on the chemical and physical composition of the atmosphere in much the same way as did the earlier Pioneer-Venus probes. Both the Probe and the Orbiter would carry ion-composition detectors, but those on the Probe may be limited to low energies. Aside from furnishing data bearing on Jovian magnetospheric physics, the Probe would yield much information of astrophysical interest, since Jupiter is believed to have a composition similar to that of the primordial solar nebula.

The challenge of the future in magnetospheric heavy-ion physics is not entirely observational. The presence of several distinct ionic species in a plasma or radiation belt serves to resurrect many important theoretical problems that had been solved for hydrogenic plasmas only. The additional constituents, for example, tend to introduce additional wave modes. This phenomenon has been studied in Vlasov theory for ion-acoustic waves[62], but a wide variety of plasma wave modes and their instabilities remains unexplored in this context. For example, drift waves (which are associated with spatial gradients in a plasma) are commonly found[78] to show maximal growth at wavelengths $2\pi/k_{\perp}$ comparable to the mean ionic Larmor radius $\bar{v}_{\perp}/\Omega$, or more specifically at $k_{\perp}\bar{v}_{\perp}/\Omega \sim 1$, as does the collisionless tearing mode (which may be relevant for the geomagnetic neutral sheet). What might be the effect of a second ionic species, having a different mean value of $v_{\perp}/\Omega$, on such instabilities? Would this create additional wave modes, or would it hybridize the modes that already existed with one ionic component? Is the peak growth rate enhanced or diminished by the inclusion of heavy ions? The answers to such questions require a serious reconsideration of drift waves and tearing modes in the multi-ion context. The effects of heavy ions on electrostatic cyclotron waves are similarly unknown and in need of investigation, as are the relationships between electromagnetic cyclotron waves involving magnetospheric heavy ions (such as O^+) and geomagnetic pulsations (such as Pc-2 and Pc-3) observed on the ground. It should be clear from these questions that much work remains to be done on multi-ionic plasma theory, and that the results of such work will be directly relevant to observations made in space.

Thus, we conclude our present review on an optimistic note. Heavy ions play an important diagnostic role in magnetospheric physics, but they also take part actively in the dynamics of the magnetosphere. They are suitable for magnetospheric injection as tracers, but they can also be used to trigger conspicuous upheavals of the magnetospheric plasma. Heavy ions are important constituents of the earth's magnetosphere, but they may be even more important in Jupiter's. The future of magnetospheric heavy-ion research (observational, experimental, and theoretical) is indeed a bright one.

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